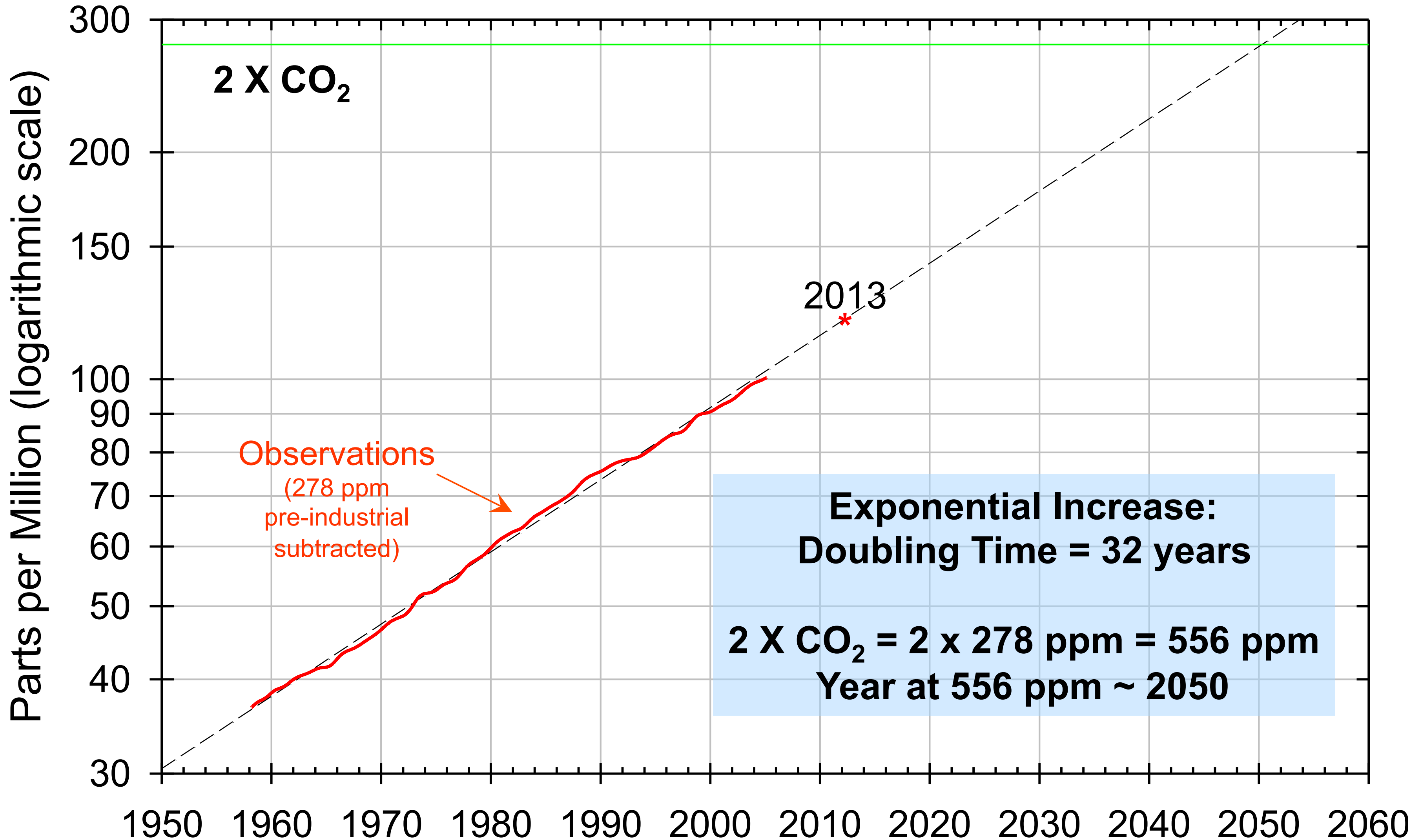
Post Industrial Carbon Dioxide Rise

When (years ago): **30** **3M** **20 M** **40 M**

Equilibrium climate: **Pleistocene** **Pliocene** **Miocene**



Slide from PNAS paper, Hofmann, et al; Solomon et al, Irreversible Climate Change, 10Feb2009; Beerling & Royer, Convergent Cenezoic CO2, Nature Geoscience, July 2011

Low Cost and Low Carbon Wind and Solar Energy Systems: Feasible with Large Geographic Size

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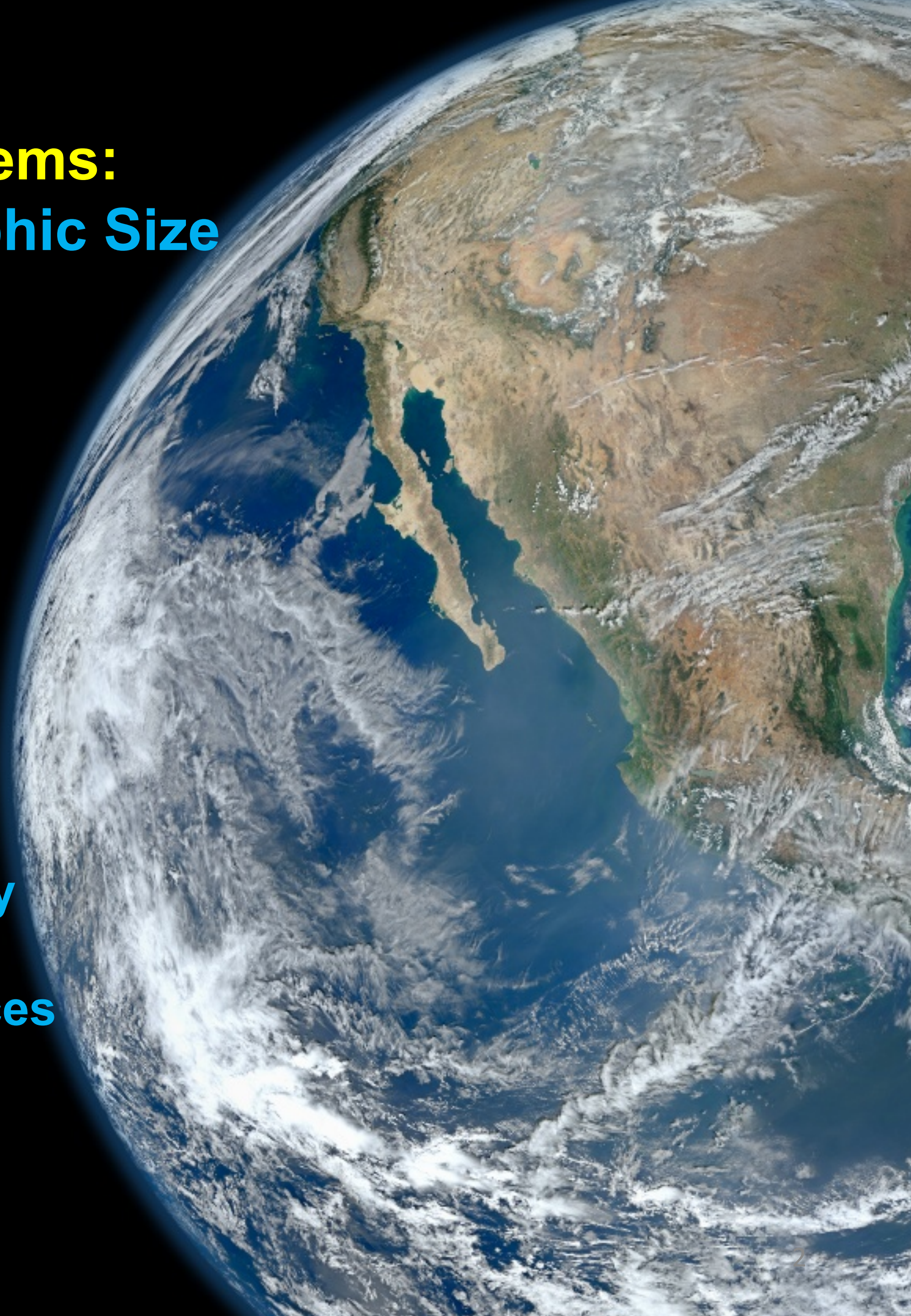
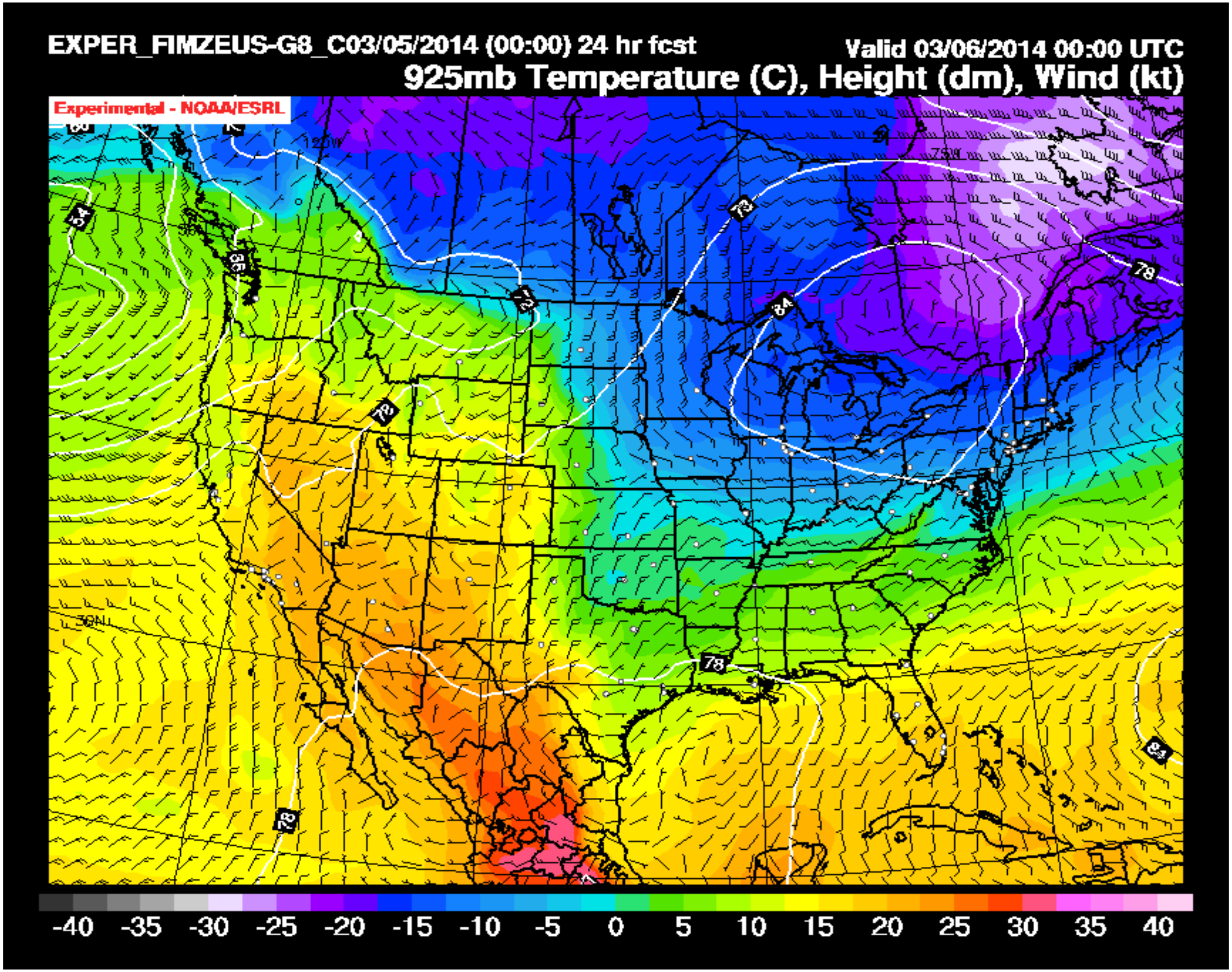
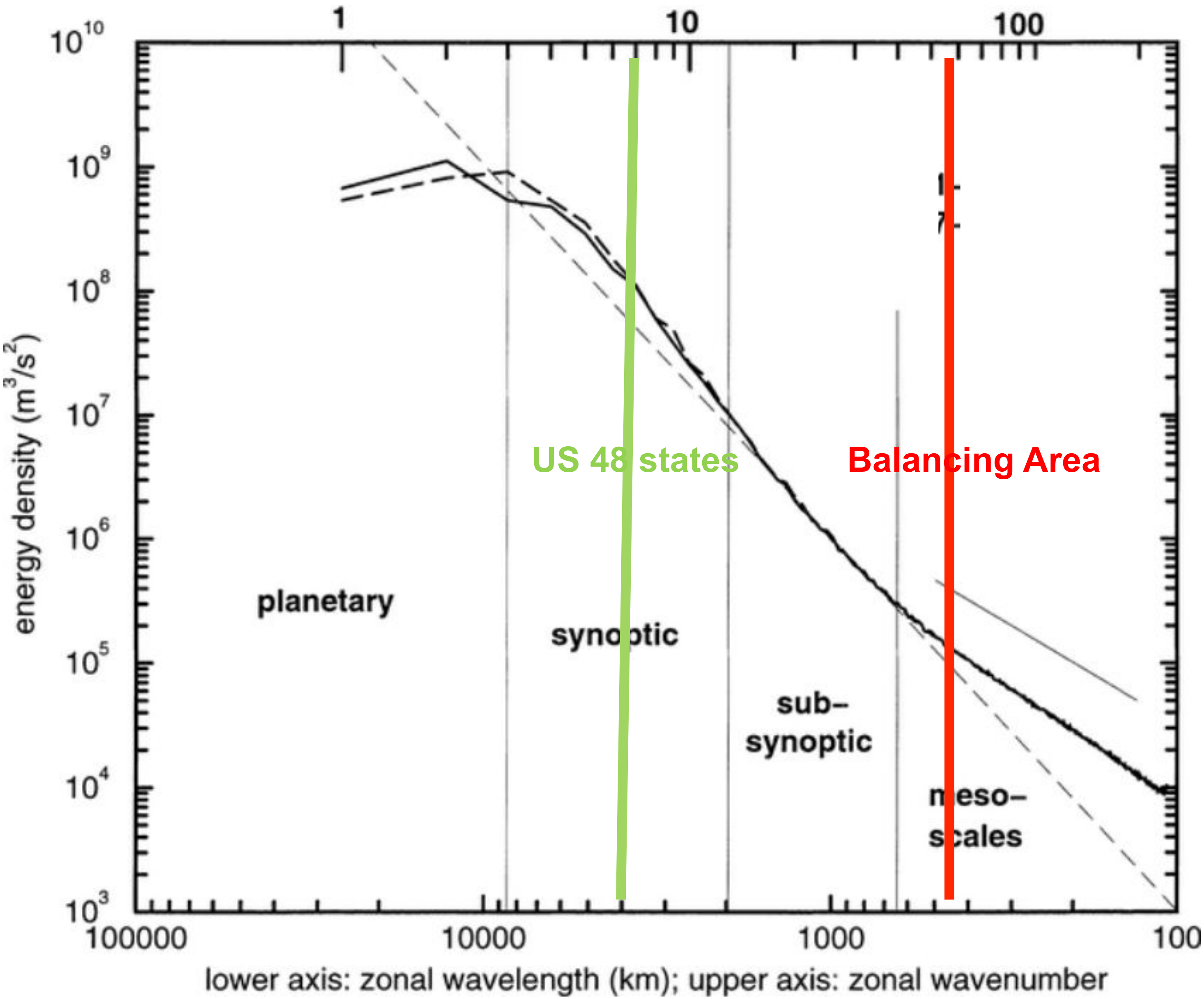




Weather is BIG. A big (cold) high covers the east, a big low comes into the west.



Spectrum of atmospheric kinetic energy density.

Weather energy is concentrated at large scales.

Low Cost and Low Carbon Wind and Solar Energy Systems: Feasible with Large Geographic Size

- We conducted a five year study to determine the geographic domain size effects of wind and solar energy generation systems.

- We built a national energy "system designer" that cost minimizes using hourly wind, solar and load concurrently.

- We conducted two studies: A detailed US Study, and a Global Study.

The Minimization Procedure

ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS

US Study: National Energy System Designer

Step 1. We collected an extraordinarily detailed and accurate weather data set.

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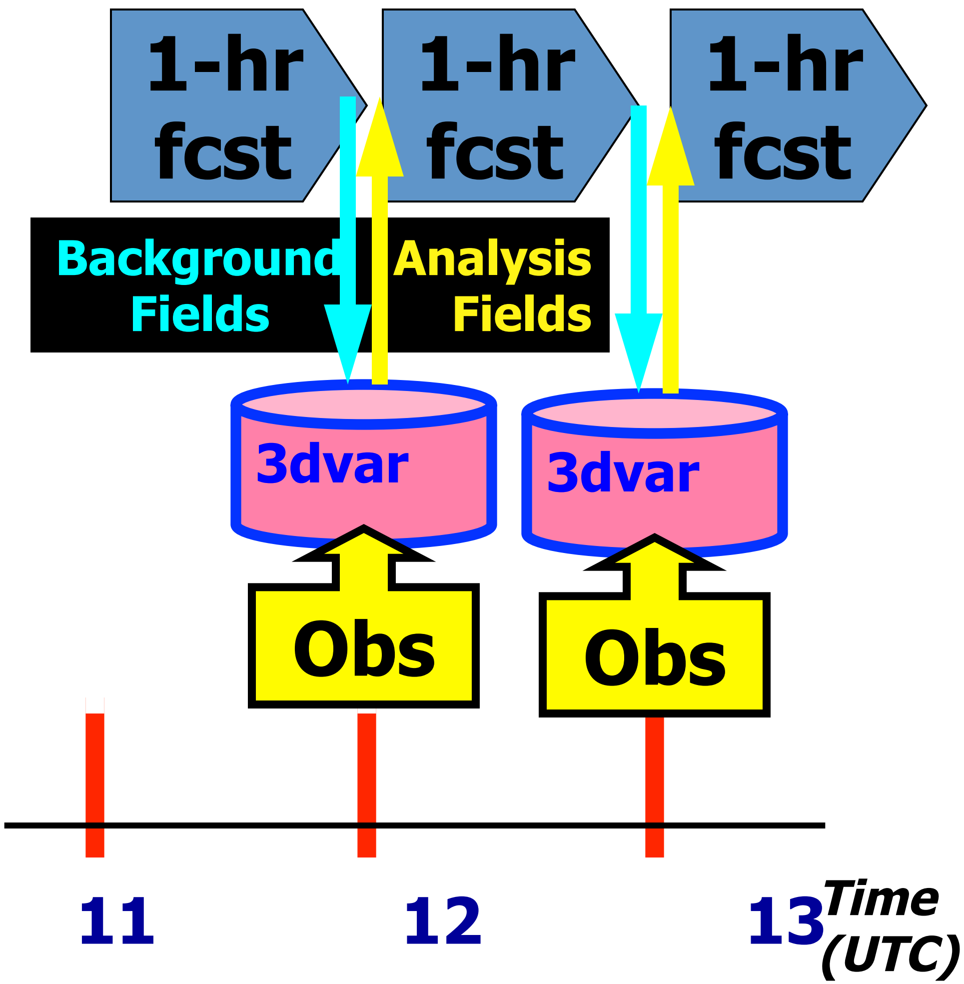
Step 4. The weather and economic simulator was used to study the technical, economic and geographic characteristics of a national system.

Rapid Update Cycle (RUC) Hourly Assimilation

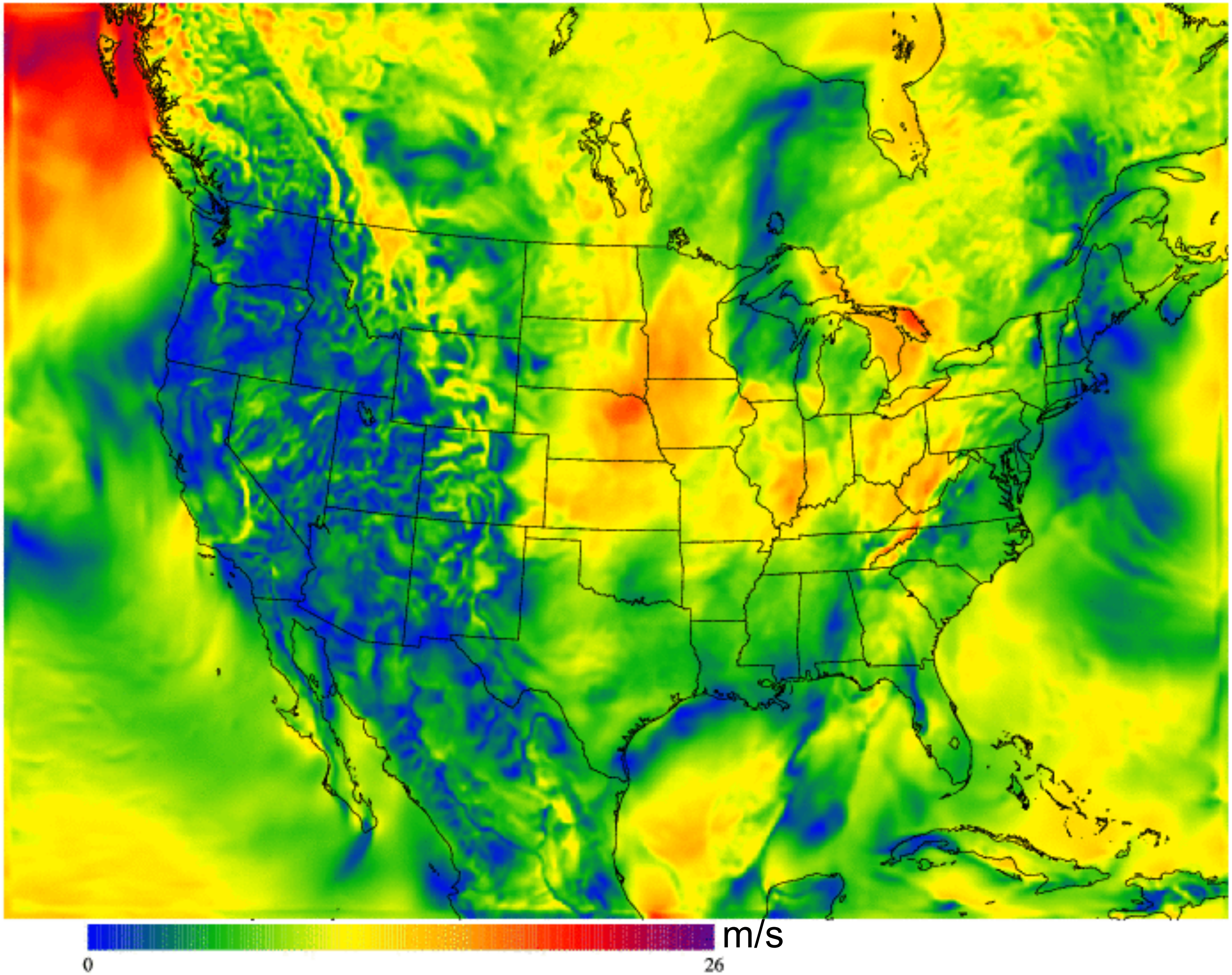
Cycle hydrometeor, soil temp/moisture/ snow plus atmosphere state variables



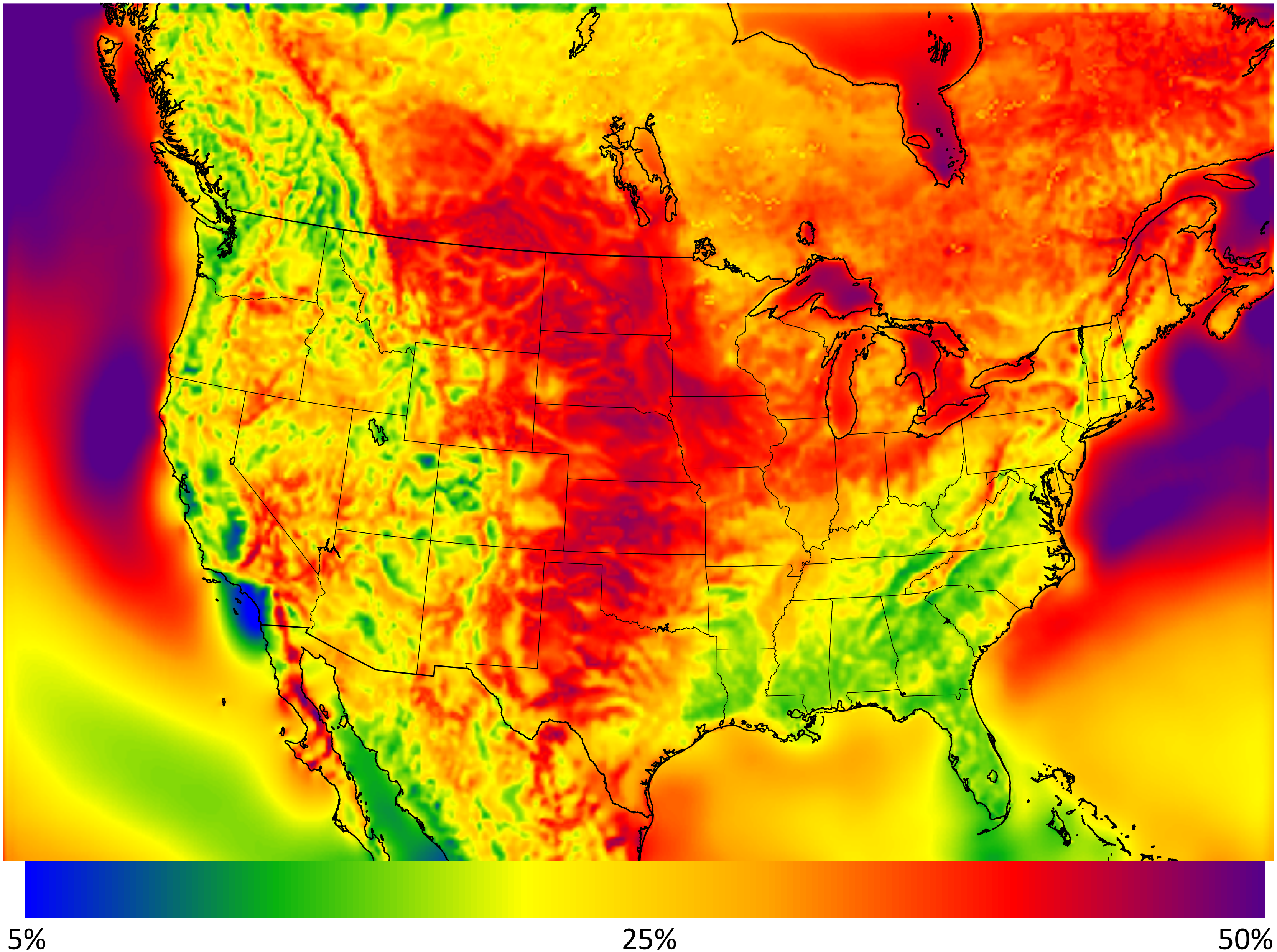
Hourly obs

Data Type	~Number
Rawinsonde (12h)	150
NOAA profilers	35
VAD winds	120-140
PBL – prof/RASS	~25
Aircraft (V,temp)	3500-10000
TAMDAR (V,T,RH) *	200-3000
Surface/METAR	2000-2500
Buoy/ship	200-400
GOES cloud winds	4000-8000
GOES cloud-top pres	10 km res
GPS precip water	~300
Mesonet (temp, dpt)	~8000
Mesonet (wind)	~4000
METAR-cloud-vis-wx	~1800
AMSU-A/B/GOES radiances – *RR only*	
Radar reflectivity/ lightning	1km

Wind Speed Video



Wind Capacity Factor Map



Getting the Solar Data Right:
Linear Multiple Multivariate Regression

$$Y_{n\times p} = Z_{n\times(r+1)}\beta_{(r+1)\times p} + \epsilon_{n\times p},$$

$$E(\epsilon_{(i)}) = 0, \quad \mathrm{Cov}(\epsilon_{(i)}, \epsilon_{(k)}) = \sigma_{ik} I, \quad i, k = 1, 2, ..., p.$$

$$\widehat{\boldsymbol{\beta}}_{(i)} = (Z'Z)^{-1} Z' \mathbf{Y}_{(i)}$$

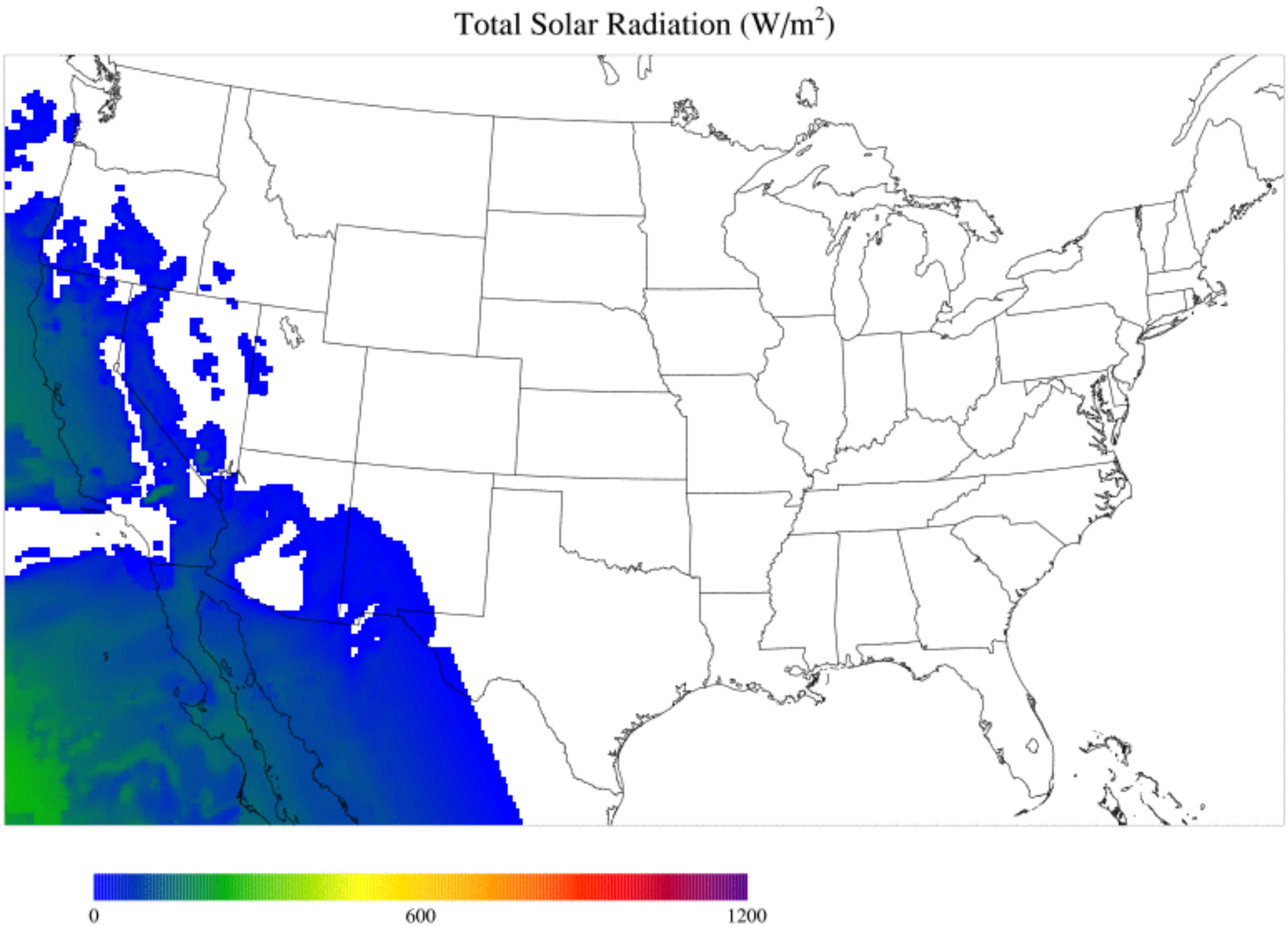
- We have p(=3) irradiance fields to calculate and n(=81,434) observation of each field. The observations are taken from 10 sites (6 SURFRAD and 4 ISIS)

- The regressors (β) are the satellite data (3 infrared channels, a visible channel, and a water vapor channel), the RUC Assimilation Model values for water within the column (snow, ice, etc…), the temperature from the model, the calculated top of atmosphere irradiance, and the zenith angle.

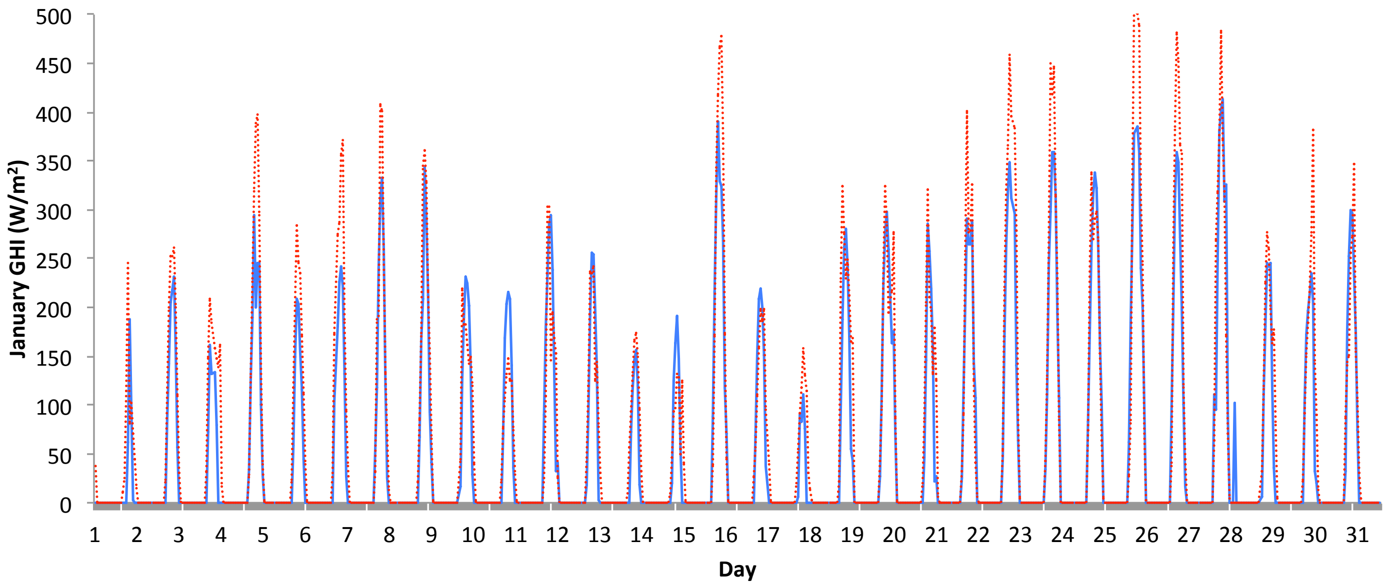
- The measurements are taken from 2006 – 2008, and averaged over the top of the hour (for 12 minutes) and matched up with the model data.

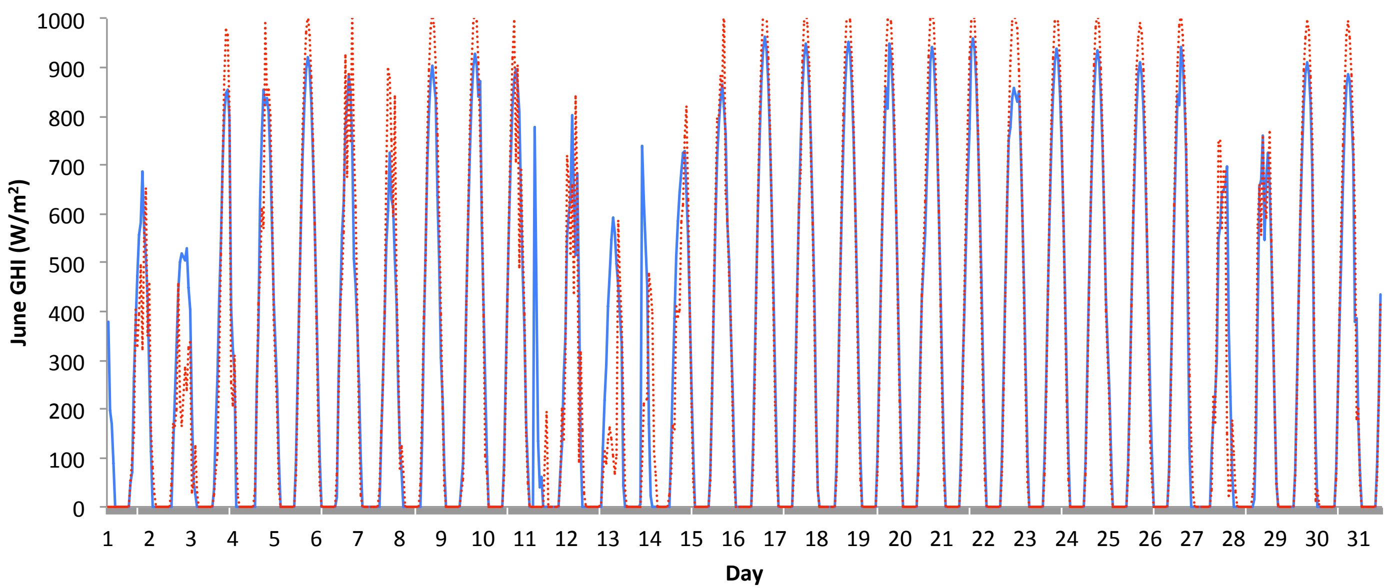
- The data is quality controlled, and all night-time measurements were removed.

Resource Video – GHI USA

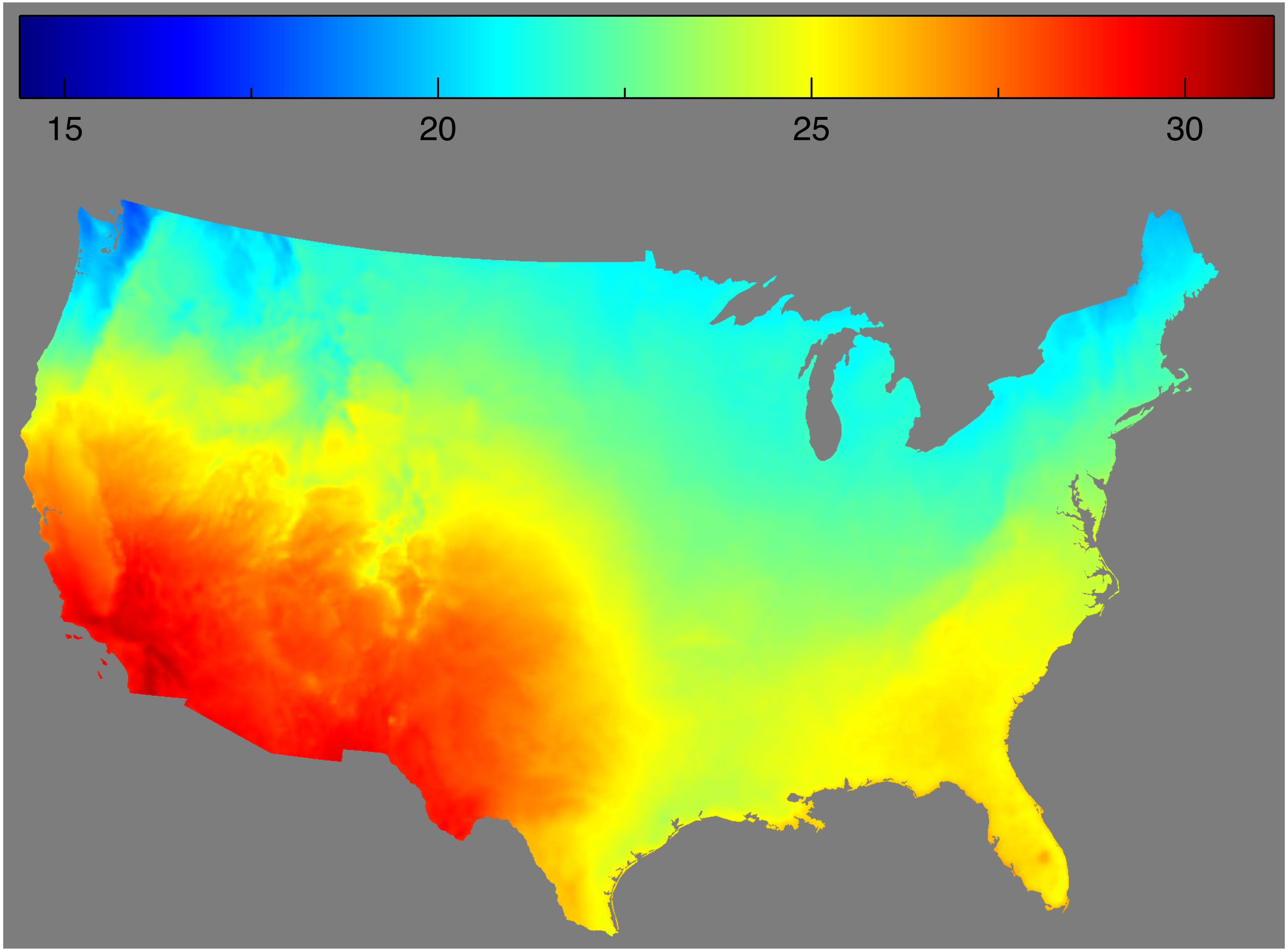


Linear Multiple Multivariate Regression





Solar PV Capacity Factor Map



US Study: National Energy System Designer

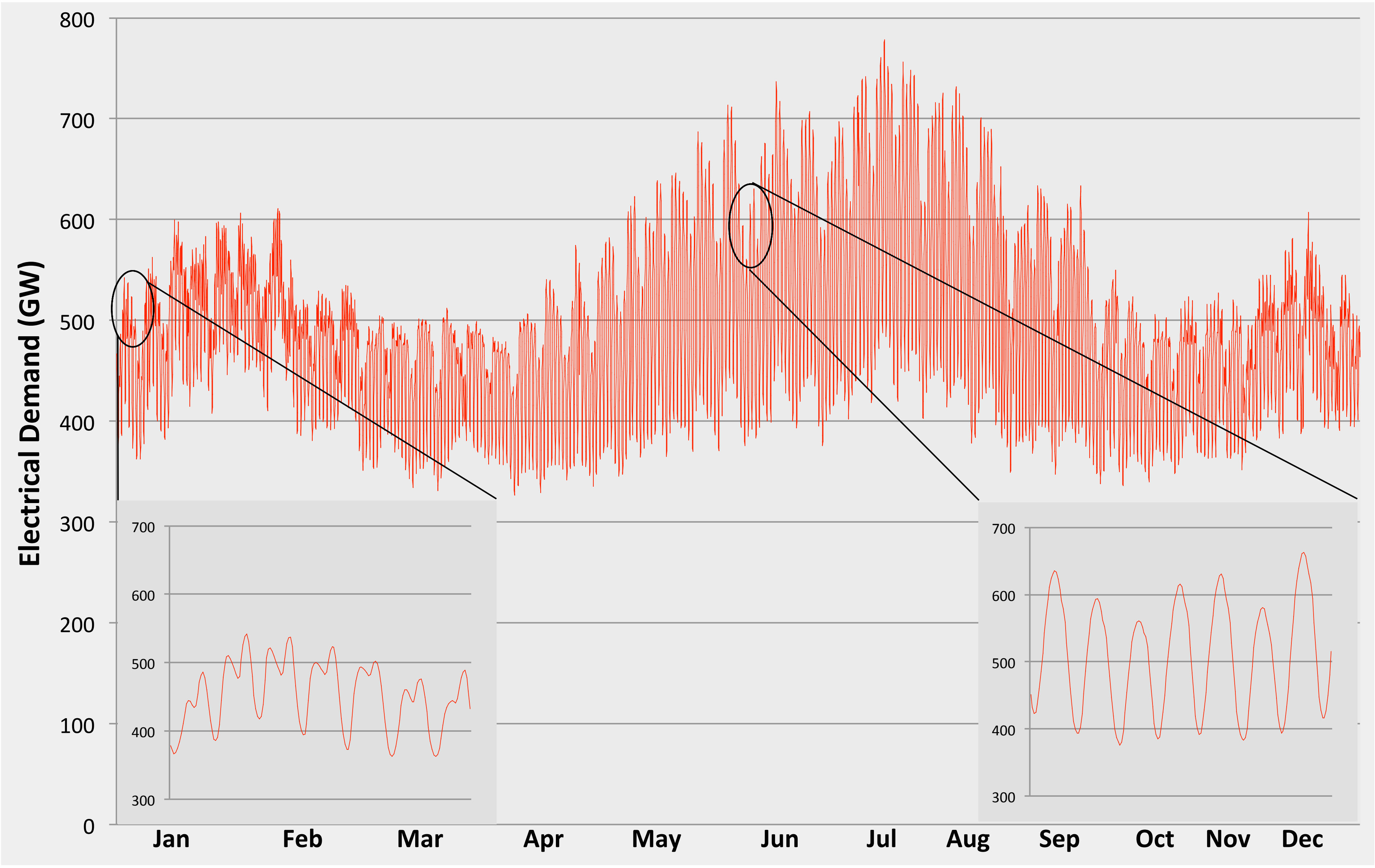
Step 1. We collected an extraordinarily detailed and accurate weather data set.

Step 2. We collected electric load data concurrent in time with the weather data.

Step 3. We developed a power system simulator that used all power sources and associated infrastructure (transmission and storage).

Step 4. The weather and economic simulator was used to study the technical, economic and geographic characteristics of a national system. (Four studies will be presented.)

Electric Demand/Load



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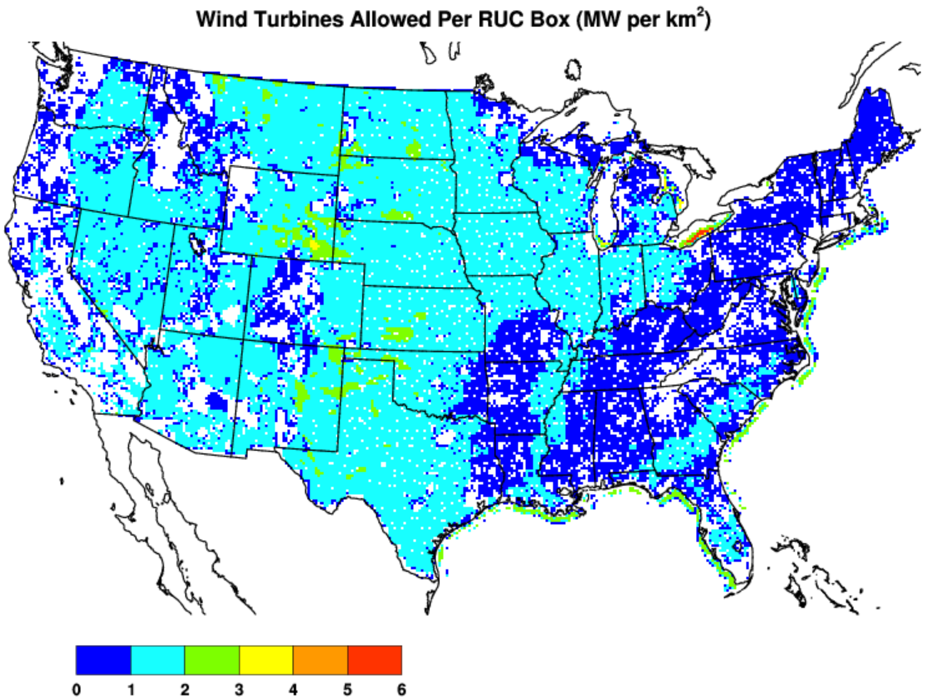
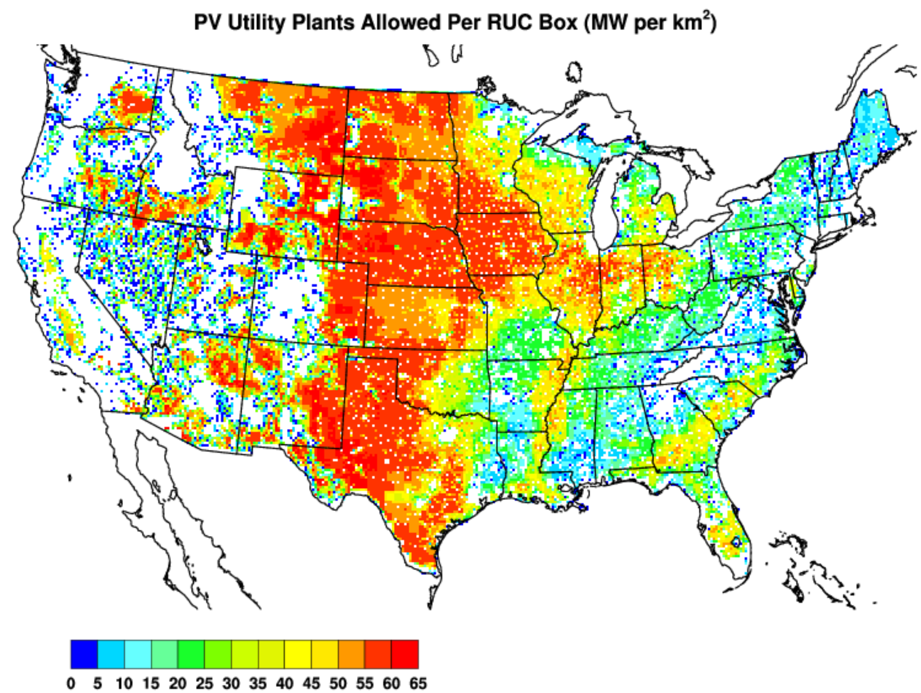
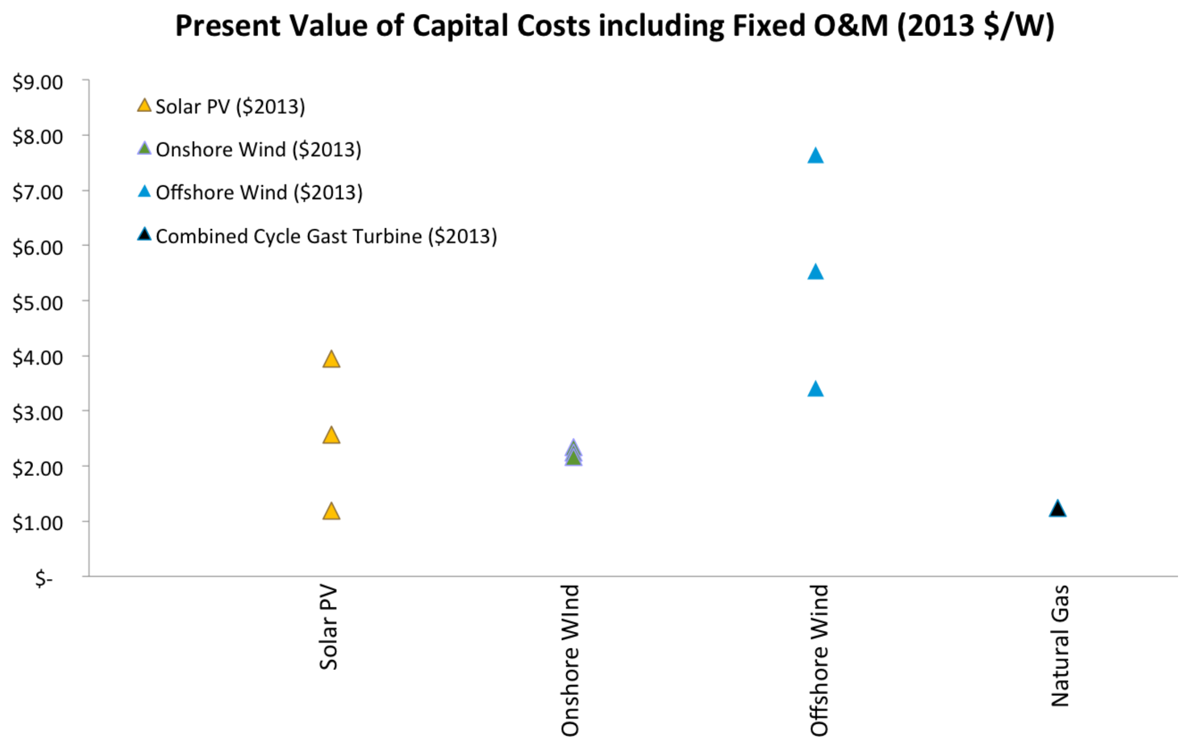
Land Use Constraints





- The type and amount of electricity generation installed in each RUC cell is constrained by:
  - **Spacing between facilities**
  - **Topography of the land**
  - **Land Use (residential, commercial, protected lands, etc…)**

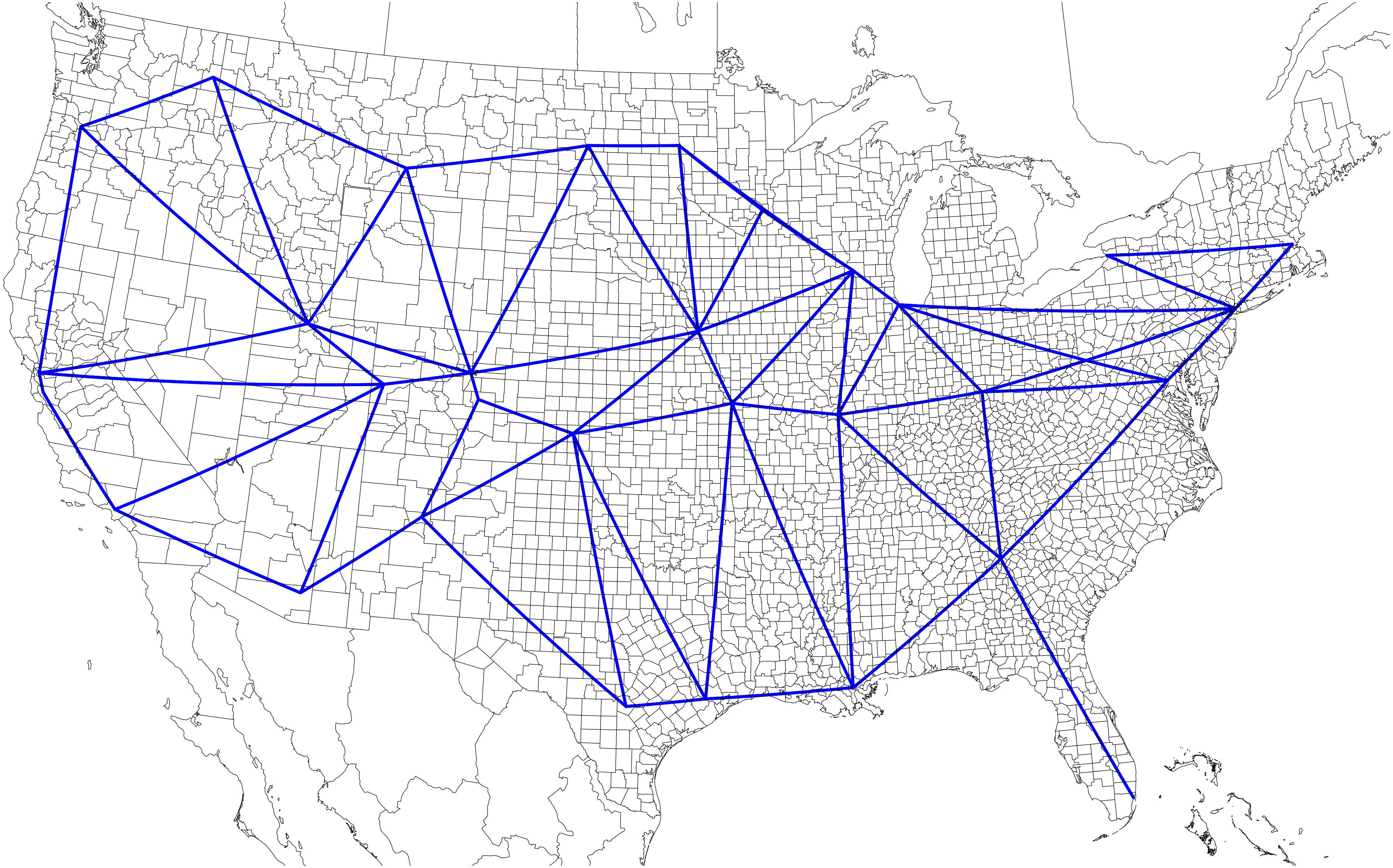
Cost Data/Values



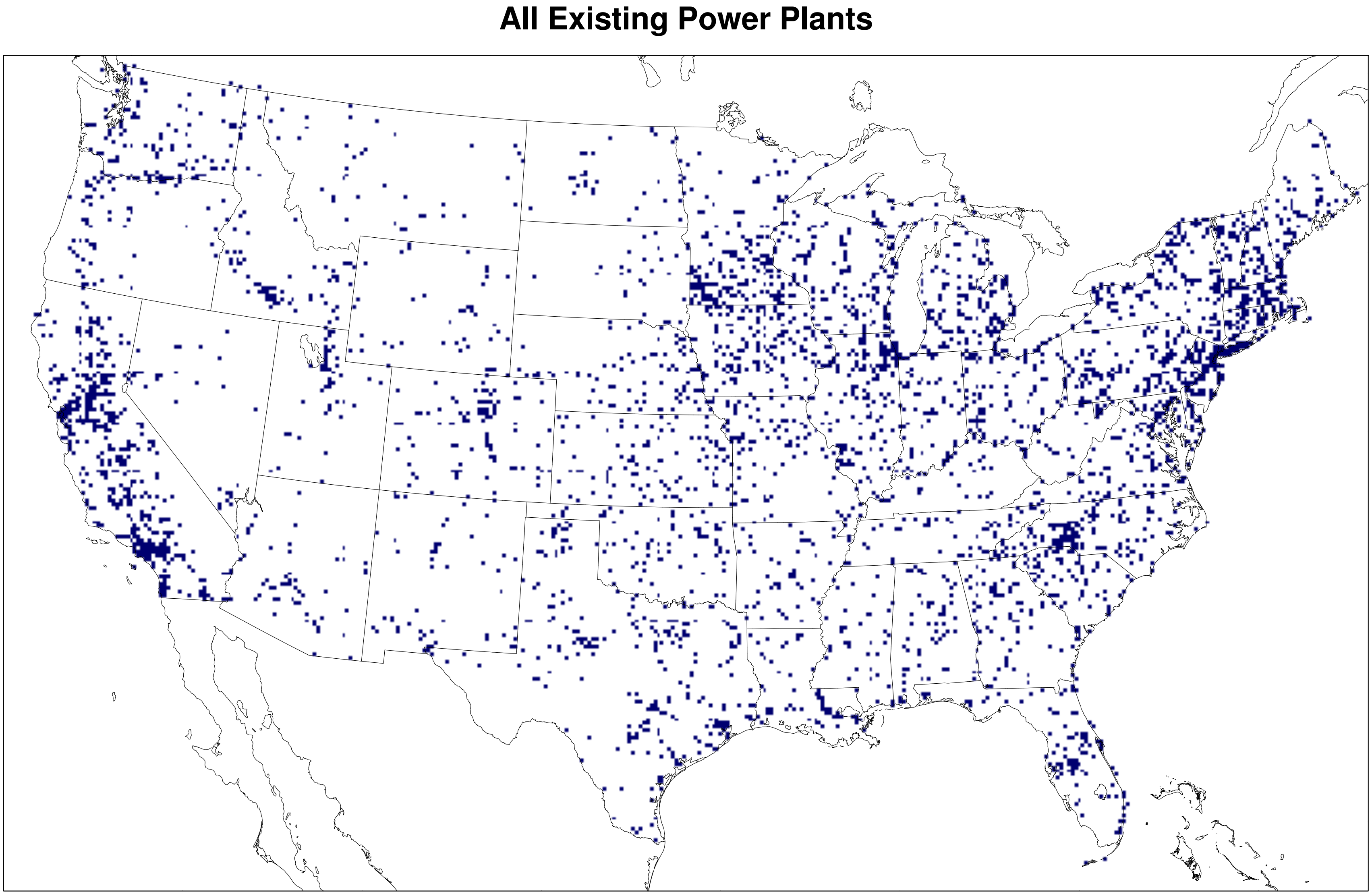
	Onshore	Offshore	PV	CCGT	NG Fuel	HVDC lines	HVDC Stations
Low W&S High NG	$2.16	$3.41	$1.19	$1.24	$11.10	$701.36	182,856.11
Mid W&S Mid NG	$2.25	$5.53	$2.57	$1.24	$8.82	$701.36	182,856.11
High W&S Low NG	$2.36	$7.64	$3.94	$1.24	$5.40	$701.36	182,856.11

Natural gas has a heat rate of 6430 Btu / kWh. Variable O&M is $3.11 / MWh

HVDC Transmission Parameterization



Existing Generators (can be) Included



Present Paper Optimization Procedure

$$\text{Minimize} \quad \psi = \sum_{\phi} \sum_{\kappa} \mathcal{C}^{v}_{\phi\kappa} \cdot V_{\phi\kappa} + \sum_{\mu} \left(\mathcal{C}^{g}_{\mu} \cdot G_{\mu} + \mathcal{C}^{f}_{\mu} \cdot \sum_{\tau} D_{\mu\tau} \right) + \sum_{\hat{\alpha}} \sum_{\hat{\beta}} T_{\hat{\alpha}\hat{\beta}} \cdot \left(\mathcal{C}^{ts} + \mathcal{C}^{tl}_{\hat{\alpha}\hat{\beta}} \cdot \delta_{\hat{\alpha}\hat{\beta}} \right)$$

Natural gas generation (MWh)

Yearly cost of transmission stations ($/MW)

Yearly cost of variable generation ($/MW)

Yearly cost of conventional generation ($/MW)

Installed capacity of transmission (MW)

Installed capacity of variable generation (MW)

Installed capacity of conventional generation (MW)

Yearly cost of transmission lines ($/MW-mile)

Cost of conventional fuels ($/MWh)

Length of transmission lines (mile)

Present Paper Optimization Procedure

Load constraint

Subject to:

$$\overbrace{\sum_{\phi} \left(b^{v}_{\phi\omega} \cdot \sum_{\kappa} V_{\phi\kappa} \cdot \mathcal{W}_{\phi\kappa\tau} \right)}^{\text{VARIABLE GENERATION}} + \overbrace{\sum_{\mu} b^{c}_{\mu\omega} \cdot \left(D_{\mu\tau} + N_{\mu\tau} + H_{\mu\tau} \right)}^{\text{CONVENTIONAL GENERATION}} = \overbrace{\mathcal{L}_{\omega\tau} - F_{\omega\tau} + E_{\omega\tau}}^{\text{NET ELECTRIC DEMAND}}, \quad \forall\, \omega, \tau$$

Variable generator Filter

Installed capacity of variable generation (MW)

Weather Component (h)

Conventional generator filter

Natural gas generation (MWh)

Nuclear generation (MWh)

Hydroelectric generation (MWh)

Electric demand (MWh)

Transmission power flux (MWh)

Excess generation (MWh)

Present Paper Optimization Procedure

VERY IMPORTANT CONSTRAINT AND EXTREMELY COMPUTATIONALLY EXPENSIVE

HVDC transmission flux constraint

Transmission power flux (MWh)

Transmission power flow (MWh)

Transmission power flow (MWh)

$$F_{\omega\tau} = \sum_{\alpha} T_{\alpha\beta\tau} \cdot (1 - \lambda_{\alpha\beta} \cdot \delta_{\alpha\beta}) \Big|_{\beta=\omega} - \sum_{\beta} T_{\alpha\beta\tau} \Big|_{\alpha=\omega} , \quad \forall\, \omega, \tau \; (\alpha \neq \beta)$$

Length of transmission lines (mile)

Electric loss factor (%/mile)

Present Paper Optimization Procedure

Transmission Capacity Bound (MW)

Transmission capacity constraint

Transmission Capacity (MW)

Transmission power flow (MWh)

$$\mathcal{T}_{\hat{\alpha}\hat{\beta}} \geq T_{\hat{\alpha}\hat{\beta}} \geq T_{\alpha\beta\tau}|_{\alpha,\beta=\hat{\alpha},\hat{\beta}} \geq 0, \quad \forall\, \hat{\alpha}, \hat{\beta}, \tau \; (\hat{\alpha} > \hat{\beta})$$

Present Paper Optimization Procedure

Planning reserve requirement constraint

Installed capacity of conventional generation (MW)

Conventional generator filter

Conventional generator filter

Planning reserve (%)

Natural gas generation (MWh)

$$\sum_{\mu} b^{c}_{\mu\omega} \cdot G_{\mu} \geq \left(1 + \mathcal{R}^{g}_{\mu}\right) \cdot \sum_{\mu} b^{c}_{\mu\omega} \cdot D_{\mu\tau} \geq 0, \quad \forall\, \omega, \tau$$

Present Paper Optimization Procedure

$$\mathcal{B}^{n-}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{N}_{\mu\tau} \right) \leq \sum_{\mu} b^{c}_{\mu\omega} \cdot N_{\mu\tau} \leq \mathcal{B}^{n+}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{N}_{\mu\tau} \right)$$

$$\mathcal{B}^{h-}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{H}_{\mu\tau} \right) \leq \sum_{\mu} b^{c}_{\mu\omega} \cdot H_{\mu\tau} \leq \mathcal{B}^{h+}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{H}_{\mu\tau} \right)$$

Nuclear and hydroelectric dispatch constraints

$$\mathcal{B}^{v-}_{\phi\kappa} \leq V_{\phi\kappa} \leq \mathcal{B}^{v+}_{\phi\kappa}, \quad \forall\ \phi, \kappa$$

Wind and solar siting constraint

$$0 \leq G_{\mu} \leq \mathcal{B}^{g}_{\mu}, \quad \forall\ \mu$$

Natural gas siting constraint

Present Paper Optimization Procedure

- Optimization has $O(10^6)$ equations, $O(10^7)$ variables and $O(10^{8\text{-}9})$ non zeroes
- Solves in $O(10^6)$ iterations or $O(10^5)$ seconds.
- We solve on two platforms:
  1. Large RAM desktop (75 GB, 1 processor)
  2. Dedicated Server with 1 TB of RAM and 32 processors

- ✔ 256 node transmission network with a nested algorithm for true optimality
- ✔ Expansion of current technologies to locations proposed
- ✔ Switching generators and heat rates when use permits it
- ✔ Concentrating Solar Power output and storage within optimization
- ✔ Multi-year investment and dispatch
- ✔ HRRR dataset for simpler power modeling for higher resolution optimization
- ✔ AC modeling of transmission within node structure
- ✔ Much more accurate solar irradiance modeling
- ✔ Including forecast error statistics as an input / stochastic optimization

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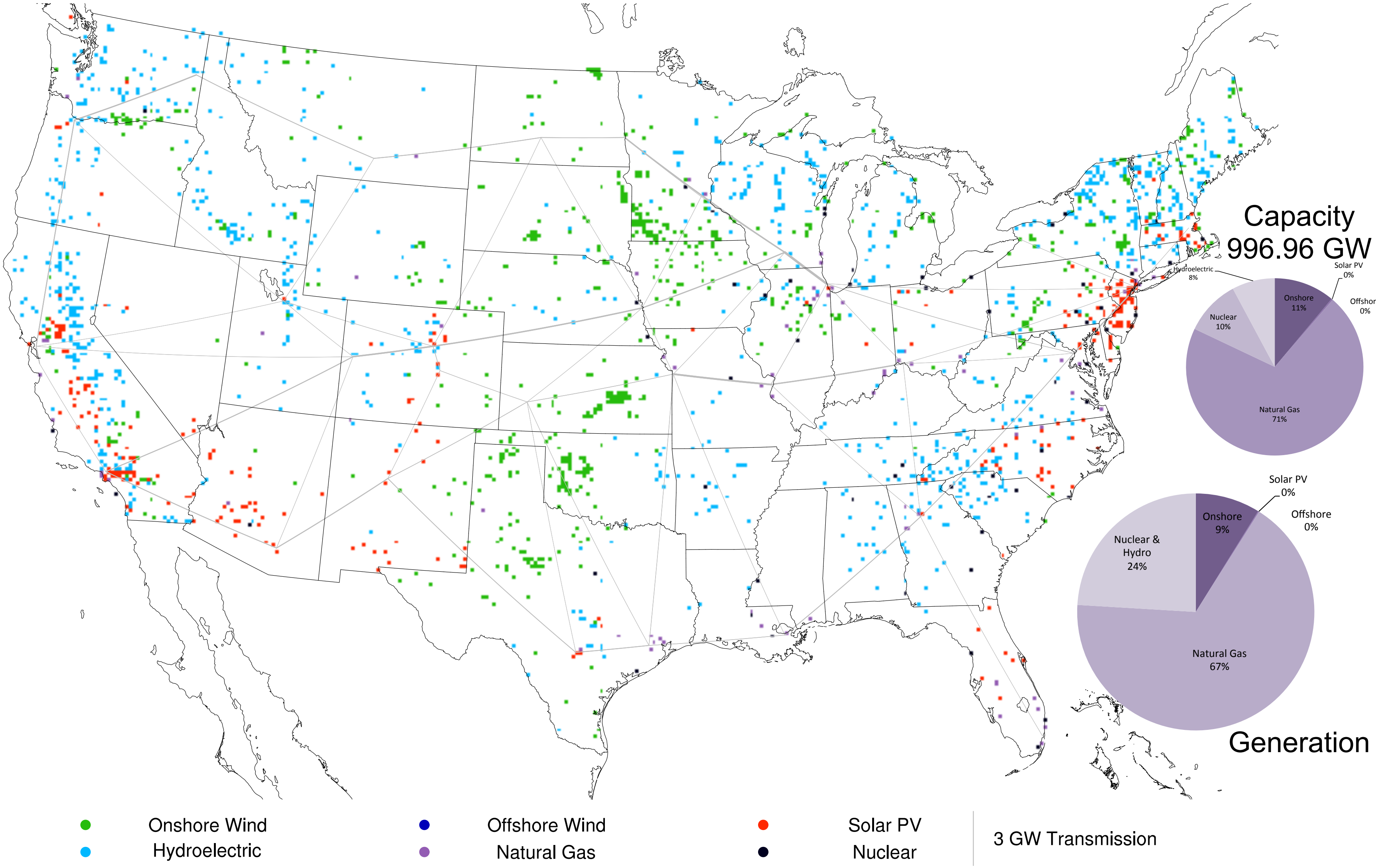
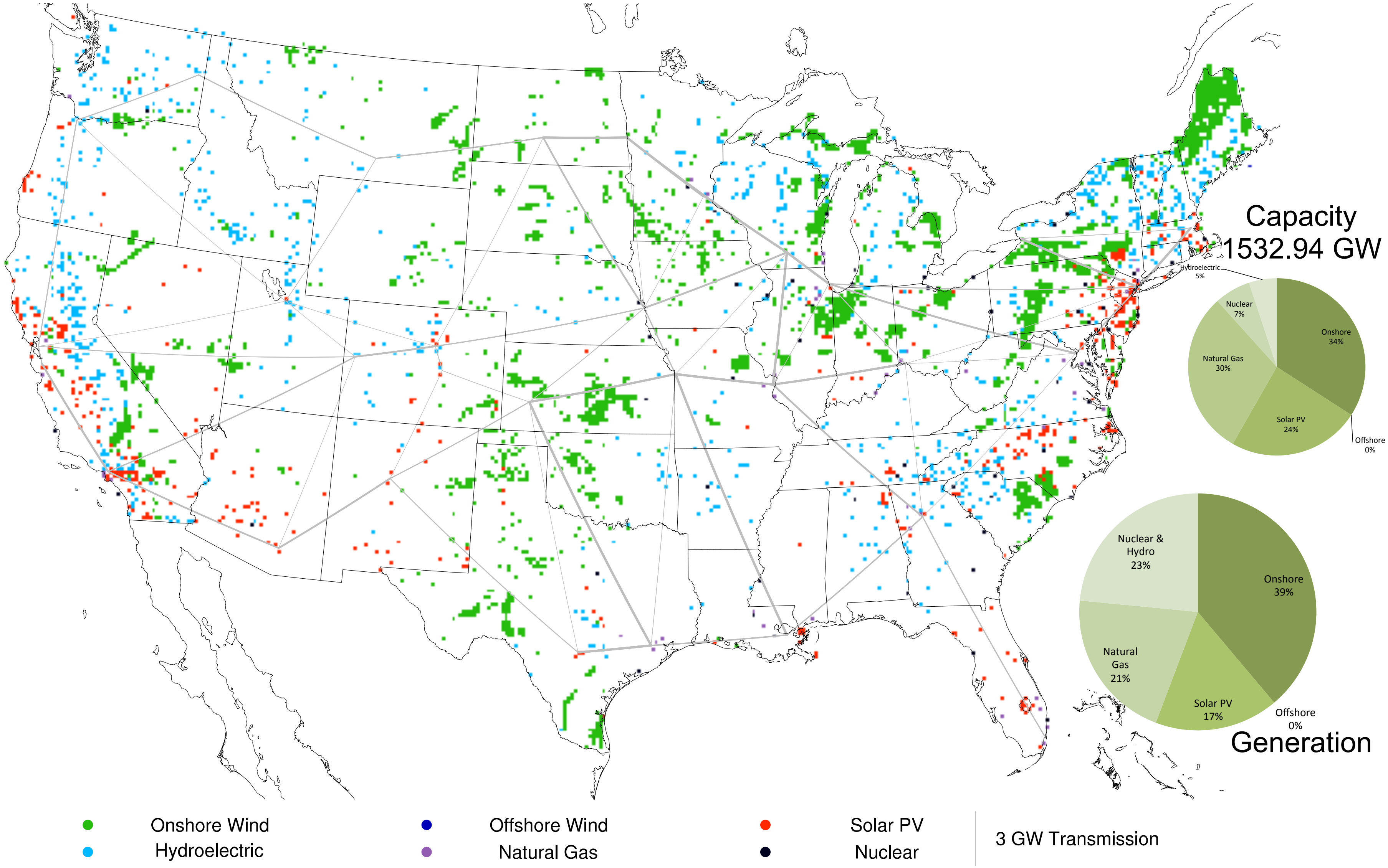
US Study Results

Cost-Optimized National Electric Power System (2007 / High RE & Low NG / 1 System)

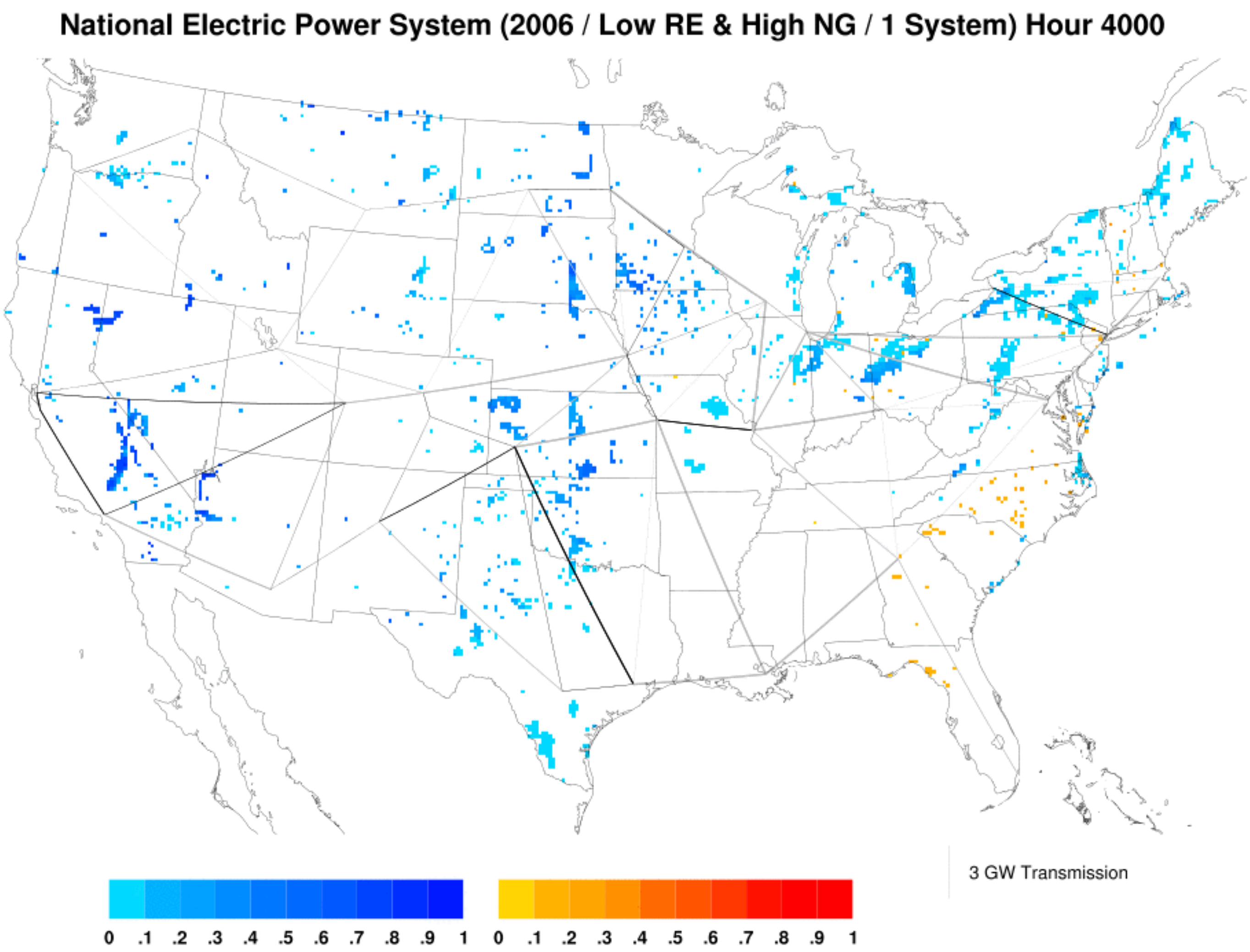


US Study Results

Cost-Optimized National Electric Power System (2007 / Low RE & High NG / 1 System)



System Realtime Simulation

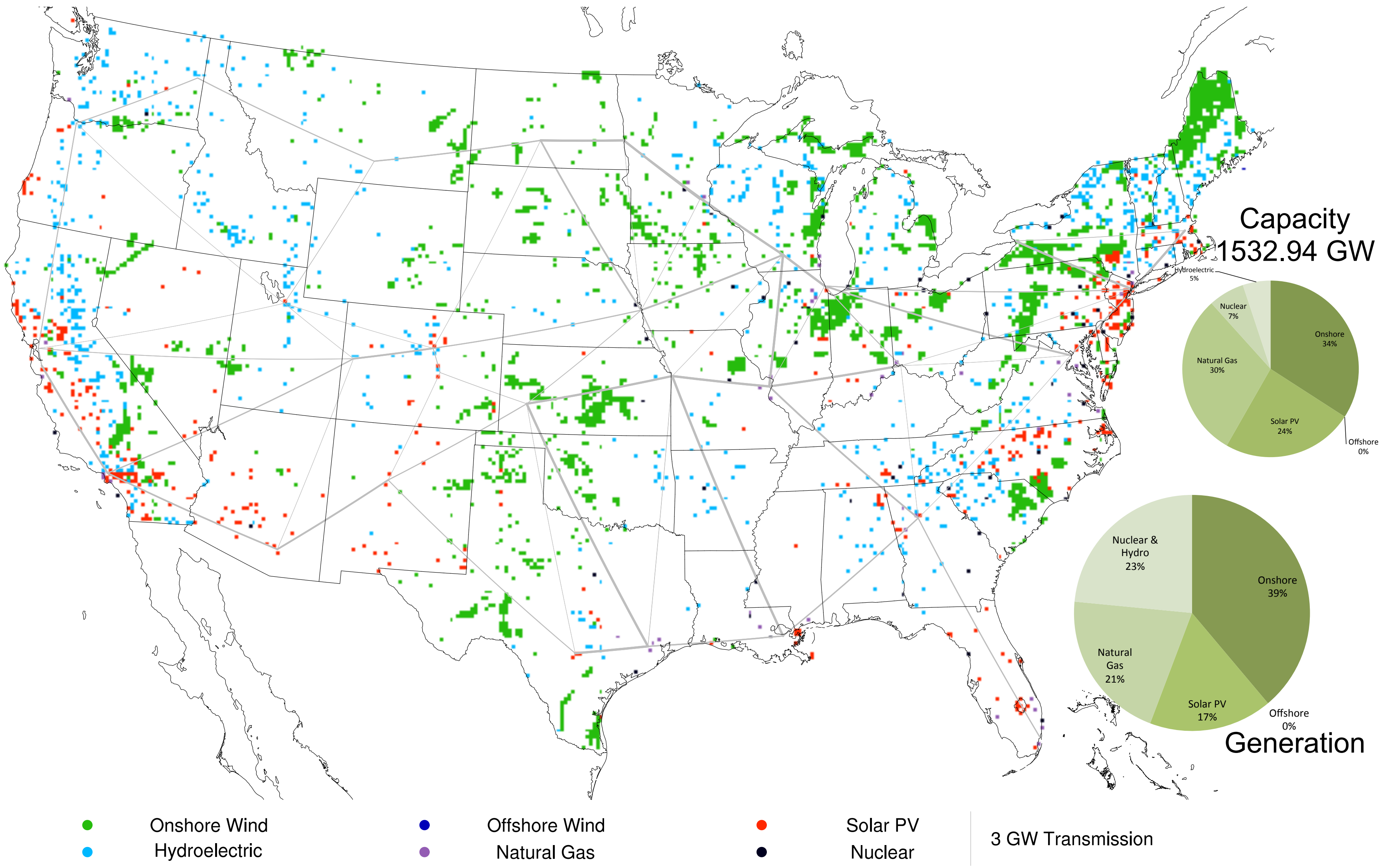


Study : Effect of HVDC Transmission

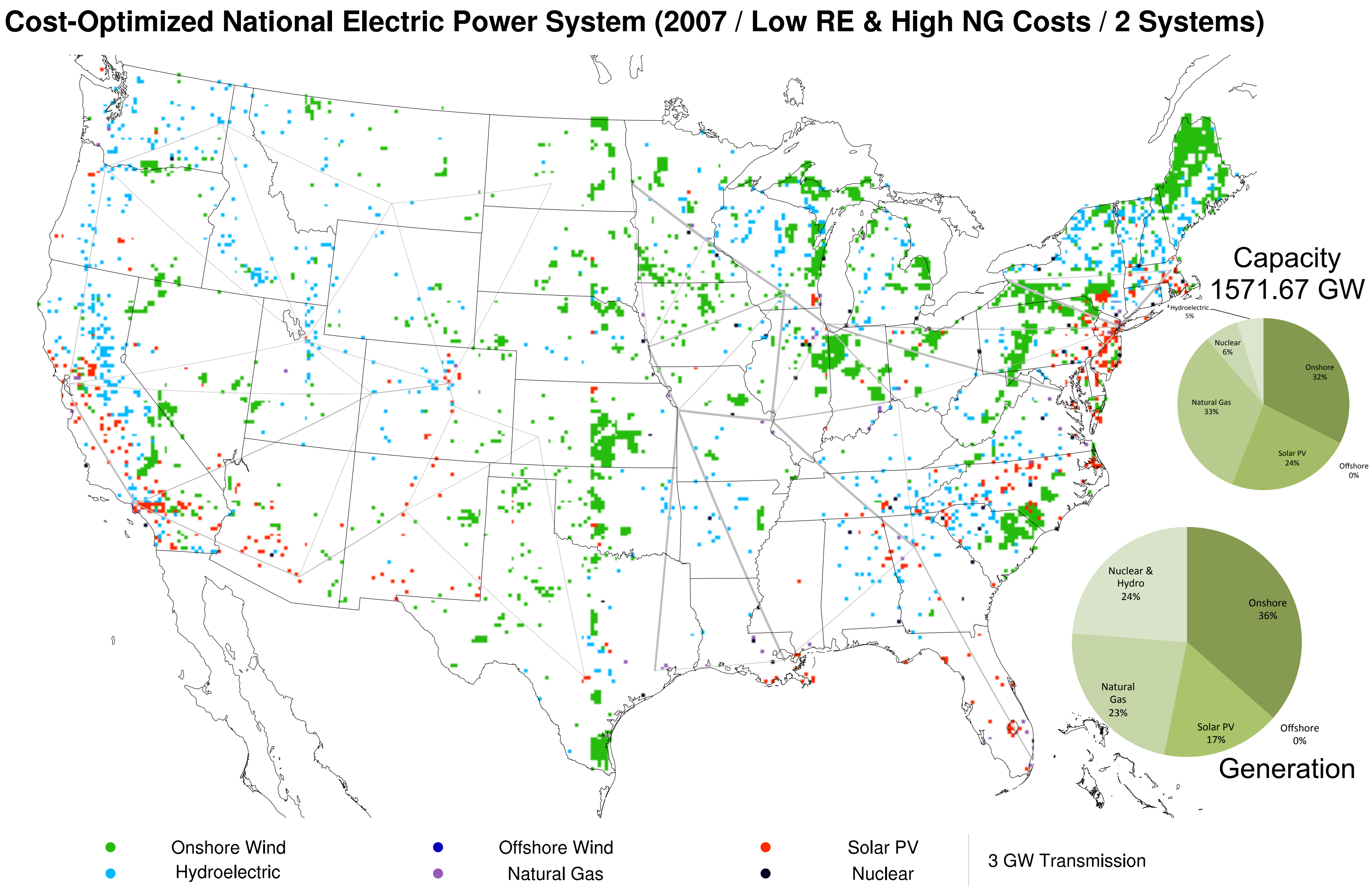
- **Scaling: Size of energy market area varied.**
- Demand projected to 2030.
- LLH = Low cost wind, solar, High-cost gas

US Study Results

Cost-Optimized National Electric Power System (2007 / Low RE & High NG / 1 System)

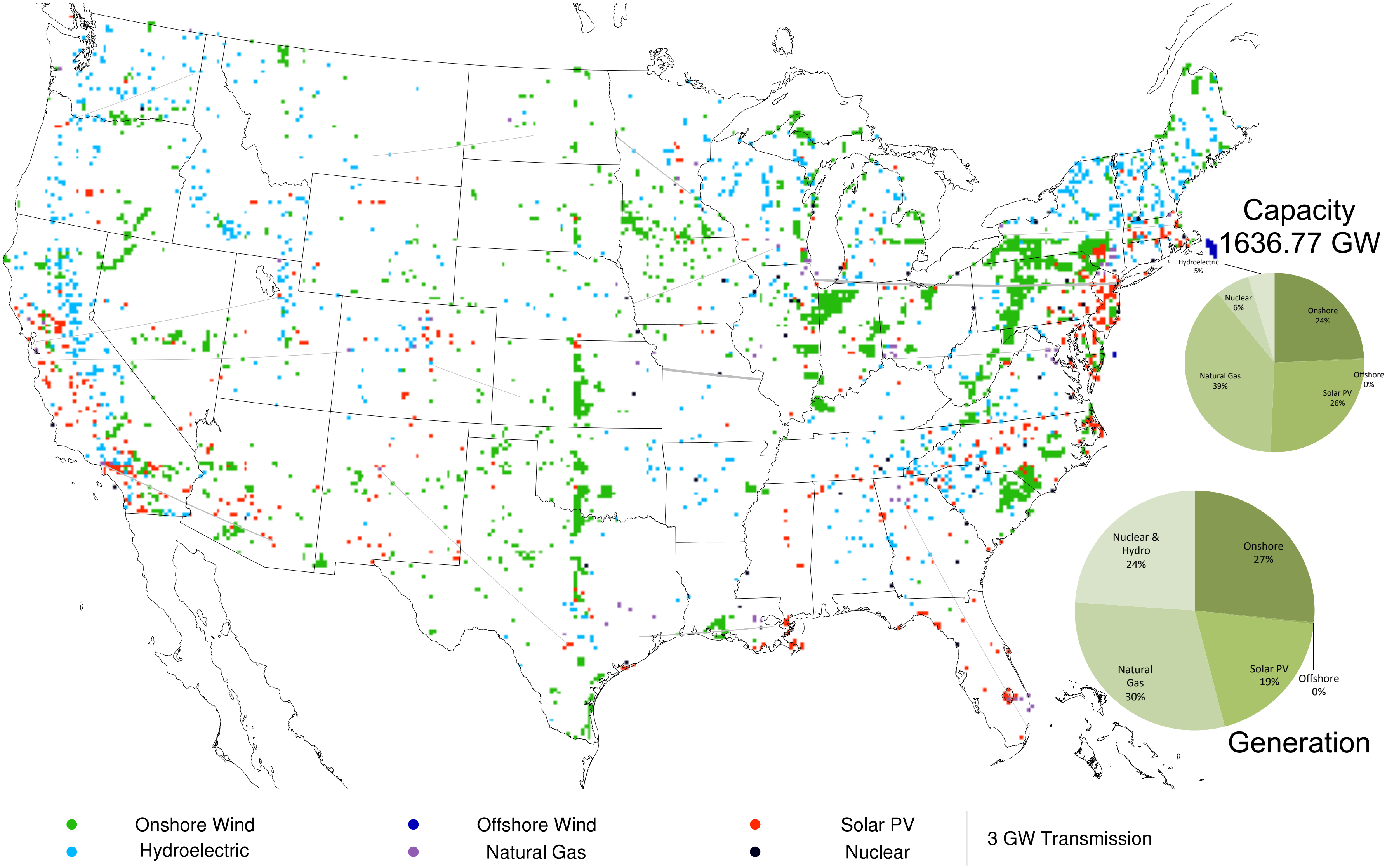


US Study Results: Half CONUS



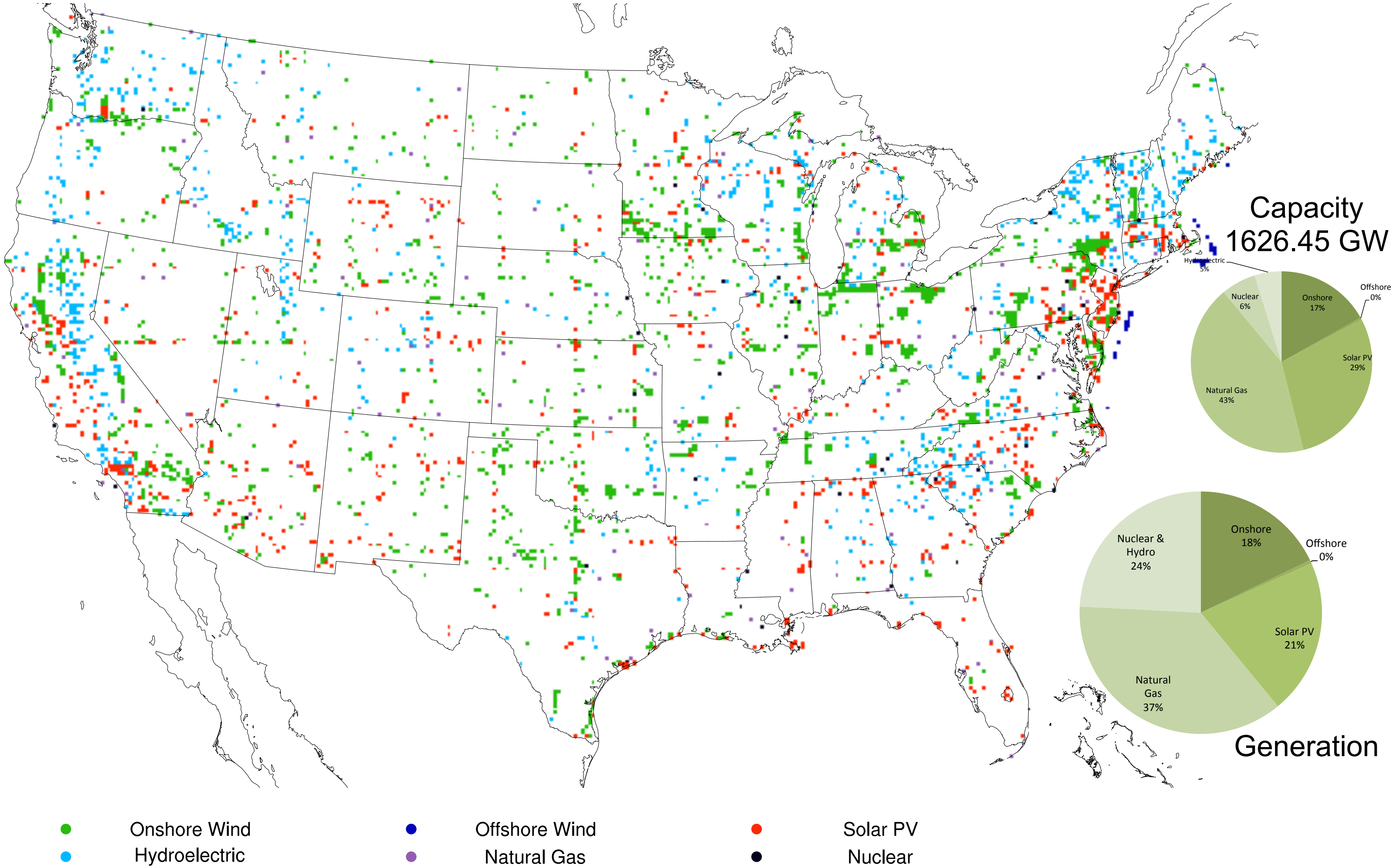
US Study Results: Sixteenth CONUS

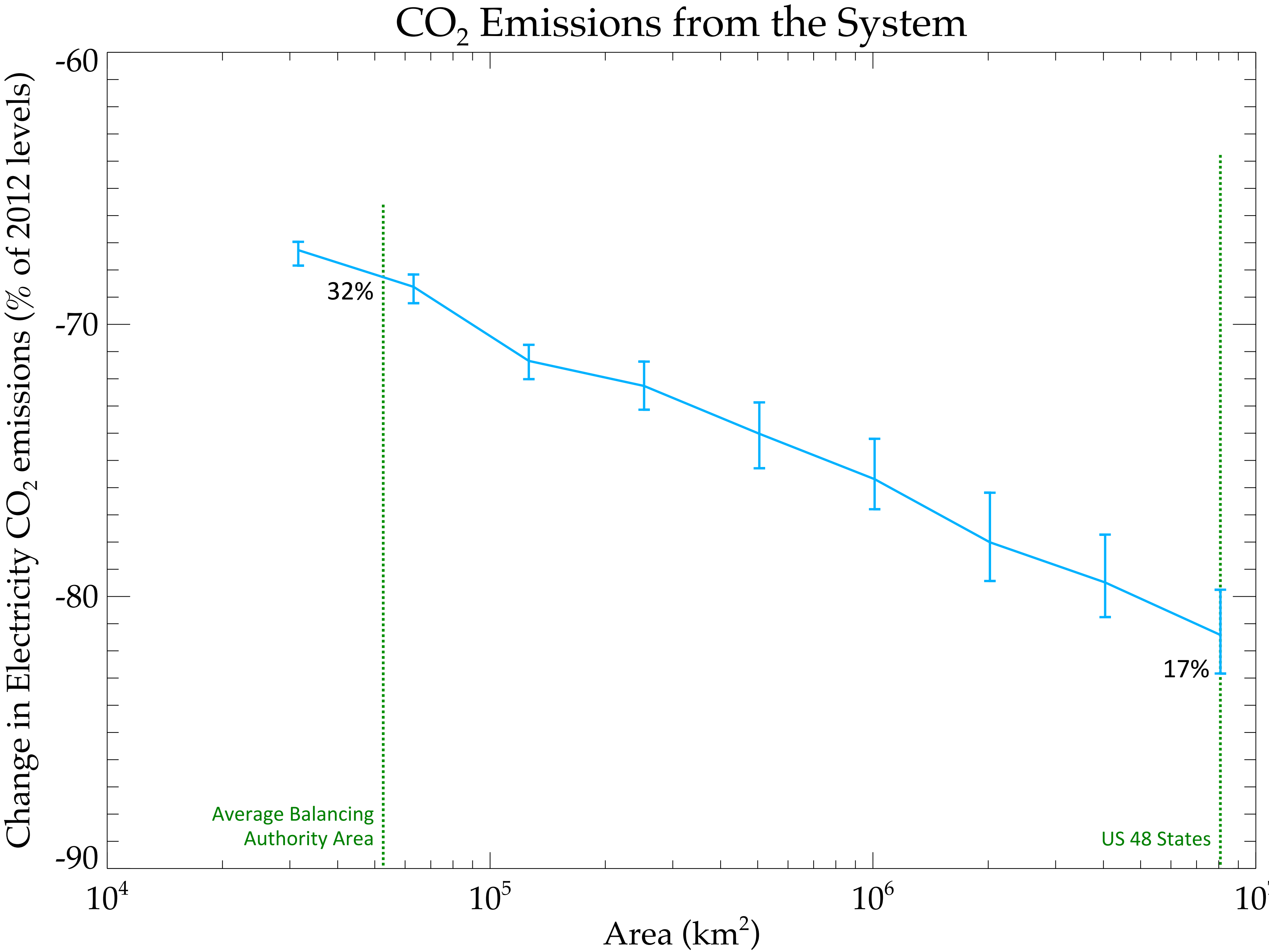
Cost-Optimized National Electric Power System (2007 / Low RE & High NG Costs / 16 Systems)

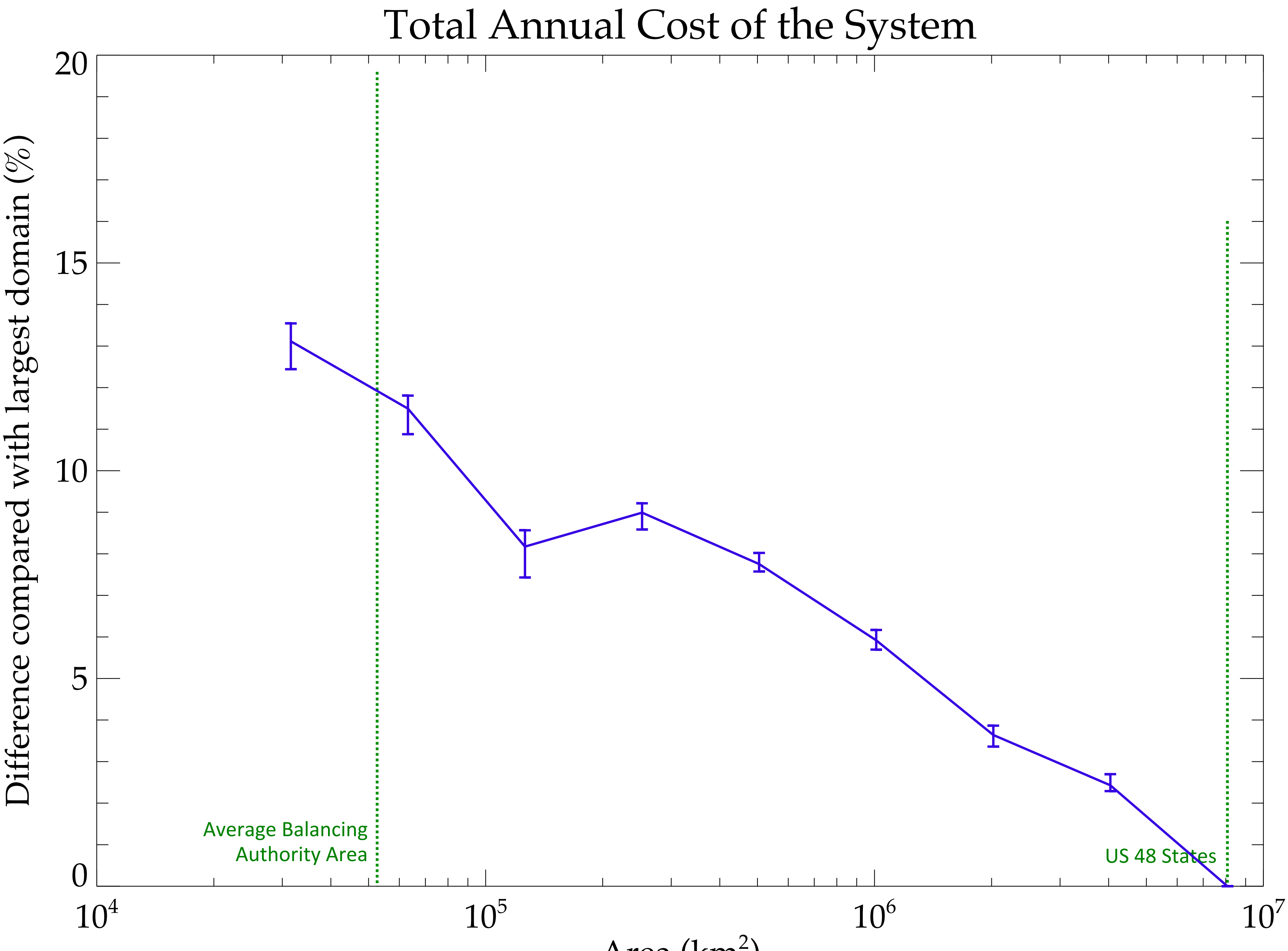


US Study Results: 128th CONUS

Cost-Optimized National Electric Power System (2007 / Low RE & High NG Costs / 128 Systems)



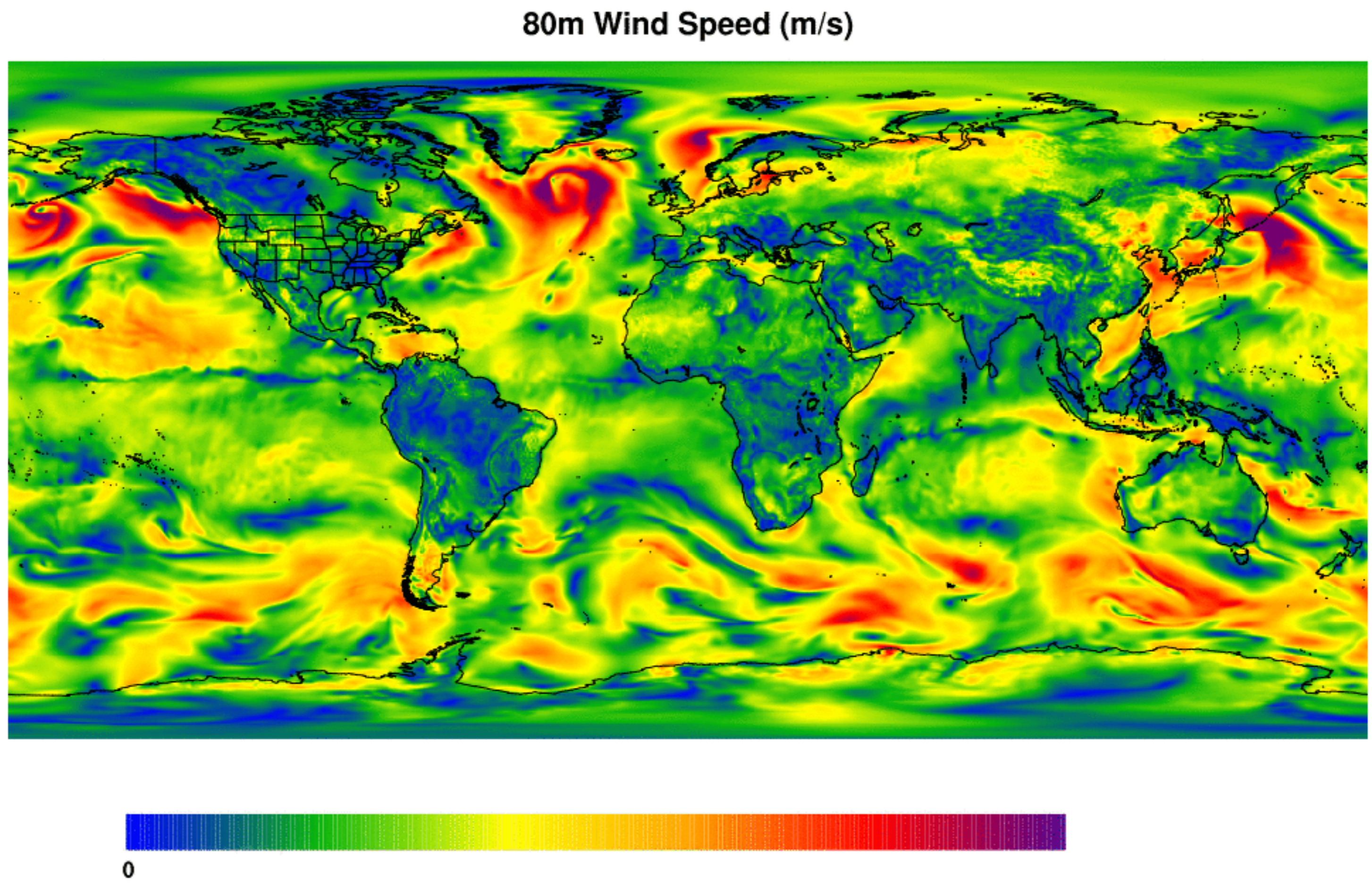

CO2 Emissions from the System
Change in Electricity CO2 emissions (% of 2012 levels)
-60
-70
-80
-90
32%
17%
Average Balancing
Authority Area
US 48 States
10^4
10^5
10^6
10^7
Area (km^2)



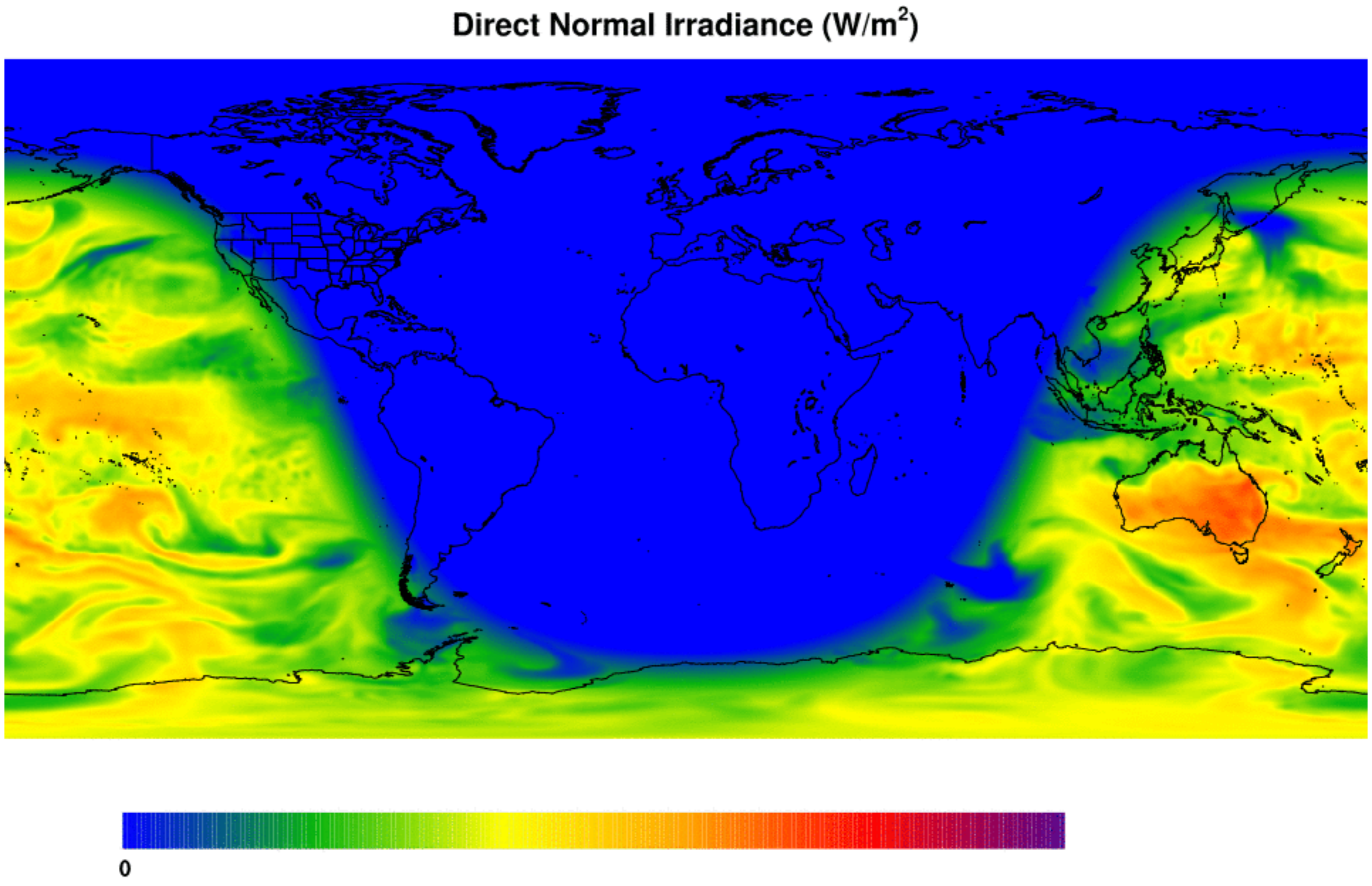
Total Annual Cost of the System
Difference compared with largest domain (%)
20
15
10
5
0
Area (km^2)
10^4
10^5
10^6
10^7
Average Balancing
Authority Area
US 48 States

Simpler Global Regions

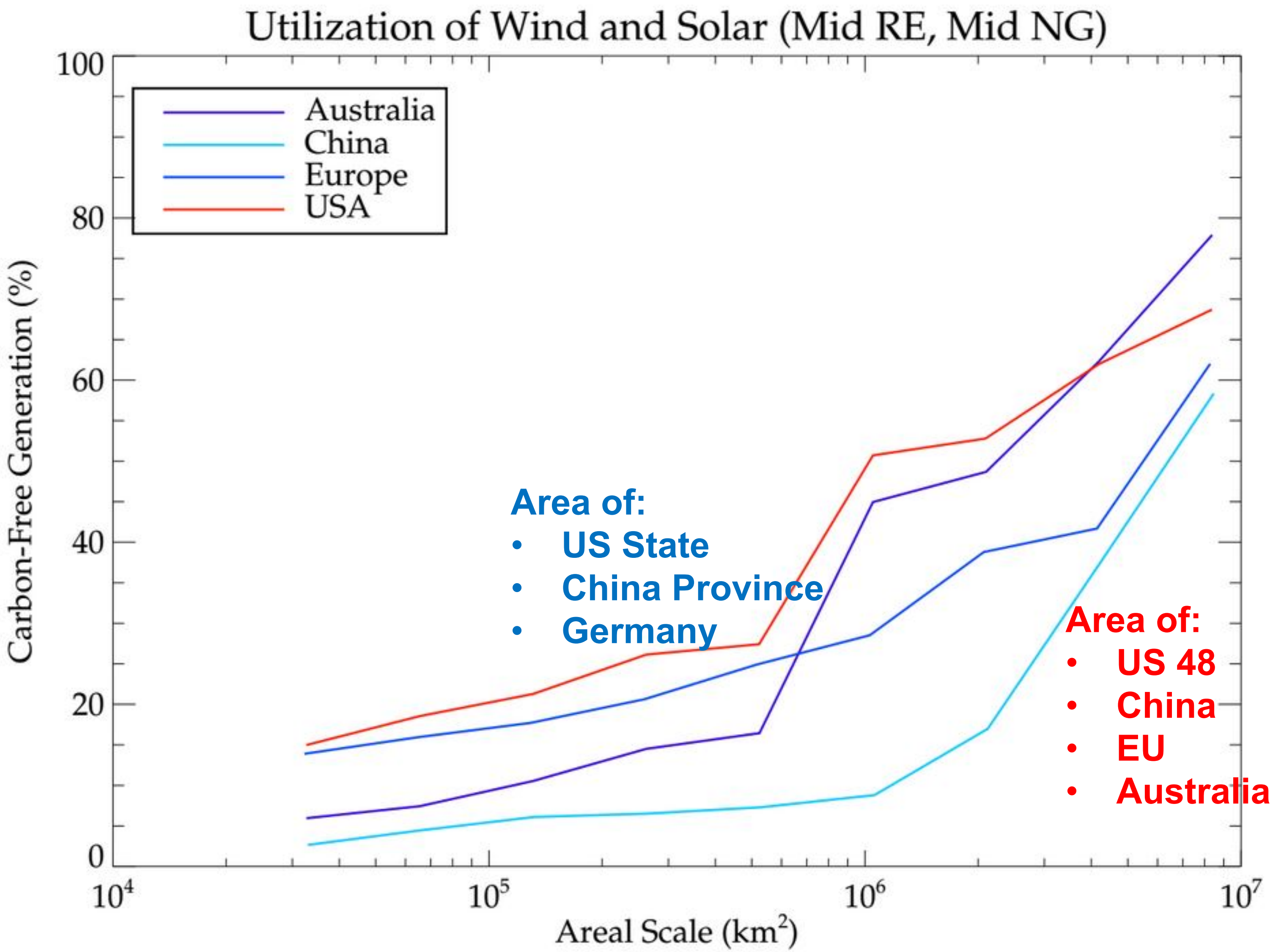
Global Resources



Global Resources



Global Study - 2030



Global carbon-free generation increases with geographic domain.

Conclusions

- Since weather is variable over large geographic scales, wind and solar generation and use must also encompass large geographic areas to be reliable and cost effective.

- An HVDC transmission grid would enable a large domain, such as the US 48 states.

- The US Study, using optimistic projections of wind and solar costs, could reduce CO_2 emissions by 82% with somewhat lower electric costs.

- The Global Study, using mid-range cost projections, shows that wind and solar energy will not play a significant role in reducing CO_2 emissions without transmission enabled large domains.


Questions . . . .